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VIBROACOUSTIC TEST PLAN EVALUATION

STUDY ON DEVELOPMENT OF COST EFFECTIVE ALTERNATE APPROACHES TO CREATING SHUTTLE SPACELAB PAYLOAD ENVIRONMENTAL TEST REQUIREMENTS

Volume 3

(NASA-CR-160076) VIBROACOUSTIC TEST PLAN EVALUATION. STUDY ON DEVELOPMENT OF COST EFFECTIVE ALTERNATE APPROACHES TO CREATING SHUTTLE SPACELAB PAYLOAD ENVIRONMENTAL TEST REQUIRMENTS, VOLUME 3 (General Electric Co.) 00/39

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FOREWORD

The study presented herein was performed by the General Electric Space Division, Valley Forge, Pennsylvania, for the Structural Dynamics Branch of the Test and Evaluation Division of NASA Goddard Space Flight Center under Contract NAS 5-20906. The study was performed in two phases:

1. Phase A, Study on Component Environmental Specification Development and Test Techniques.

2. Phase B, Study on Development of Cost Effective Alternate Approaches to Creating Shuttle Spacelab Payload Environmental Test Requirements.

The principal investigator was Harold R. Gongloff and the Program Manager was Clyde V. Stahle. The NASA technical monitors were W. Brian Keegan and Joseph P. Young who provided valuable guidance throughout the course of this study. This report is presented in three volumes:

Volume 1 - "Study Overview" summarizes the results of the complete study.

Volume 2 - "Study on Component Environmental Specification Development and Test Techniques" presents the results of the Phase A study, including the statistical representation of the environment and a preliminary evaluation of test levels.

Volume 3 - "Study on Development of Cost Effective Alternate Approaches to Creating Shuttle Spacelab Payload Environmental Test Requirements" presents the results of the Phase B study, describing the cost optimization of seven test plans.

SUMMARY

This report presents the results obtained from the Phase B portion of this study to optimize Shuttle Spacelab payload test requirements such that design defects can be corrected in a cost effective manner. In this portion of the study, statistical decision theory is used to evaluate the cost effectiveness of seven alternate vibroacoustic test plans and to determine the optimum test levels associated with each plan. The test plans include component, subassembly and payload testing and combinations of component and assembly level testing. Major emphasis is placed on the development of the methodology for subsequent evaluation of Shuttle Spacelab payloads.

The methodology used in developing a decision model to evaluate the expected cost of a shuttle payload program using the alternate test plans is presented. The environment during ground testing and flight is represented as a log normal distributed random variable including spatial variations evaluated during the Phase A portion of this study and flight to flight excitation variations estimated from launch vehicle acoustic measurements. The vibroacoustic strength of payload components is also treated as a log normal distributed random variable using the results of previous studies. Using a stress-strength type of statistical analysis, the probabilities of component failure during testing and flight are estimated considering the test program to significantly change the component strength distribution. The effect of the test environments on the component strength accounts for cumulative damage and incipient failures. These probabilities are then used to establish the probability of achieving a completely successful or partially successful flight using a reliability model of the payload at the component level of assembly. By combining the probabilities of flight and test failures with their estimated costs, the expected program cost is estimated. The decision model treats the test levels as parameters to enable the best test plan and associated test levels to be determined.

In developing the methodology a number of simplifications and assumptions are made. The study is restricted to facility type payloads of varying complexity all of which are planned for 15 missions. At the component level of assembly the system is represented by a reliability model consisting of a series of singly redundant "housekeeping" components with one or seven experiments in parallel with the series components. For those test plans including component tests, all the "housekeeping" components are prototype tested. The payload environment is considered to have a 97.7 percentile overall acoustic level of 145 dB which is the main source of payload excitation. Equally effective tests for components, subassemblies or the complete payload are considered but a more accurate simulation of the flight environment is obtained from assembly testing. The cost of designing components for increasing vibration levels is not explicitly included but is reflected as a redesign/retest cost which is the same regardless of when a component failure occurs. The cost of failures is based on parallel testing of components and all but one subassembly. The cost of failures during the test of one subassembly and the system is based on overall project costs resulting from schedule slippage. The cost of flight failures is based on the cost of losing a portion of the experiment data and the subsequent cost of refurbishing the payload. One half of the duration of the flight vibration environment is used to estimate the flight failure probability. These simplifications are used to expedite decision model development.

The optimum test levels which provide a minimum project cost are determined and the test plans ranked according to cost and reliability. For all of the payload configurations, the test plan rank starting with the plan that resulted in minimum cost is:

1. Subassembly testing only
2. System testing only
3. Component and subassembly testing
4. Component and system testing
5. Component and system testing including a structural development model
6. Component testing including a structural development model
7. Component testing only

Large variations in the cost using the various test plans are indicated with the largest variation being approximately $6 Million. The lowest cost approach eliminates component testing and maintains a high flight vibroacoustic reliability by performing subassembly tests at a relatively high acoustic level. However, current contractual relations with component suppliers would have to be modified to realize the large cost reduction predicted by the model. An alternate plan which is not evaluated but appears attractive is to use protoflight component testing and subassembly testing.

It is recommended that the study be continued. Although the results obtained are considered to be representative, there are some modeling revisions that should be made. Alternate test plans including protoflight component and assembly level testing as well as a no-test option should be included. Sensitivity analysis should be performed to evaluate the effect of key parameters. The resulting decision models should be used to examine methods of reducing program costs for various payload configurations.

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SECTION 1

INTRODUCTION

The need for cost effective payload development methods intensifies as continued budget pressures are exerted on space programs. All areas are being examined to determine ways in which costs can be reduced. Without the loss of reliability the area of standardization and commonality offers potential reduced costs. These concepts are being used in the design and accommodations provided by the Spacelab. In the past the emphasis has been on maximizing spacecraft reliability, but the current trend is to accept increased risk, which is not well-defined, for reduction in cost.

The environmental test portion of spacecraft programs is one area of potential cost reduction. Although environmental testing consumes only 5 to 15 percent of the total spacecraft cost, it has been recognized that studies in this area are essential since these environmental tests provide the final assurance of flightworthy designs and hardware, Reference 1. A number of studies using decision theory in the area of cost effectiveness of environmental testing have been performed. The analyses of Stahle (Reference 2) and Thomas (Reference 3) are used in this study.

The Space Transportation System possesses a large payload volume and weight capability, the unique feature of servicing in space and/or returning payloads to earth, and the ability to fly developmental payloads on sortie missions. As a result, the payloads that will be carried on the shuttle have a wide variety of characteristics. The size of these payloads ranges from the Explorer type payloads to the large laboratory type payloads. The Space Transportation System is designed to launch 65000 pounds of payload and return 32000 pounds of payload. On a given mission the shuttle could transport a single well-defined payload or several different payloads. A single mission is likely to have a variety of mission objectives so that the consequences of a payload malfunction will vary. The multiple mission use of shuttle payloads will also influence the consequences of a payload malfunction. The problems associated with this variety of payload characteristics have been examined in the previous payload study (Reference 4).

The objective of this study is to develop cost effective alternate approaches to creating Shuttle Spacelab payload environmental test requirements. Statistical decision theory is applied to the evaluation of the seven vibroacoustic test plans shown in Figure 1-1 which describes the level of assembly that tests are performed. At the component (black box) test level a "mix" of prototype (test dedicated) and protoflight (flight) components is considered. At the higher assembly levels only protoflight testing is done. In the context of this study, the term subassembly implies a group of functionally related components mounted on a common substructure that is testable at that level of assembly. System implies a fully integrated payload. The component tests are considered to be random vibration, which provides a good simulation of effects of acoustics at this level of assembly. At subassembly and system levels, acoustic testing, which provides a good simulation of the flight conditions, is considered to be performed. In accordance with present practices, any test failure will result in redesign and retest, so that the tests serve as a screen to remove marginal designs or hardware from the payload system. The plans involve the evaluation of the change in vibroacoustic reliability of the system as a result of one or two ground tests at the various assembly levels.

Test Plan No.	Component Test	Subassembly Test	System Test
1	Mix		
1A	Mix	SDM* Only	
2	Mix	Protoflight	
3	Mix		Protoflight
3A	Mix	SDM Only	Protoflight
4		Protoflight	
5			Protoflight

*Prototype Structural Development Model

Figure 1-1 Vibroacoustic Test Plan Matrix

The scope of this study is restricted to enable the effort to concentrate on the development of the methodology needed to evaluate alternate environmental test plans. The vibroacoustic environment is the environment addressed. The acoustic environment of the STS Payload Accommodations document (145 dB) is applied. Large multi-mission facility type payloads are considered. Structural test options are directed toward the static load carrying capability of the primary structure and does not consider dynamic loading of secondary equipment mounting structure.

To evaluate the final system vibroacoustic reliability, the probability of subsequent system flight failures must be determined. Having determined the probabilities of various failures during test and flight for each of the seven test plans, the costs of the various failures can be combined with their probabilities to determine the expected program cost for a selected test plan. The test plan minimizing the sum of the expected cost and the direct testing costs will then be the optimum plan for payload testing. The major effort is directed toward a statistical decision model involving the vibroacoustic reliability of the typical payload. This is supplemented by a structural subsystem model that is directed toward an evaluation of the reliability of the payload primary structure.

In order to develop realistic decision models and costs the payload characteristics need to be identified. For this program a typical payload model is used, since the major objective is to develop a method to minimize Shuttle Spacelab payload costs. After this is accomplished and the decision models exercised, the influence of various payload configurations can be assessed at a later date.

For this study, a payload similar to the 1.5M Cryogenically Cooled IR Telescope, shown in Figure 1-2, has been considered to develop the typical payload model. The available Shuttle System Payload Data (SSPD) data sheets for this astronomy payload are provided in Reference 5. On the basis of a review of the available payload description and experiment/equipment matrix information on this payload and other Spacelab payloads, the following payload parameters have been selected as representative for this study:

Payload Weight	7500 pounds
Payload Length	15 feet
Number of Missions	15 (2 per year)
Number of Housekeeping Components	16
Number of Experiments	1 or 7
Number of Components per Experiment	2 or 6
Number of Housekeeping Sub-assemblies	3
Housekeeping Components	Prototype
Experiment Components	Protoflight

In this description, the payload is considered to consist of a basic housekeeping section and an experiment section. Further, the housekeeping section is considered to have single redundancy. This description will be clarified in the subsequent sections of this report. It will be noted that there are a large number of variables which will influence the optimum cost. In order to concentrate on the development of the methodology, the above parameters were fixed in this study.

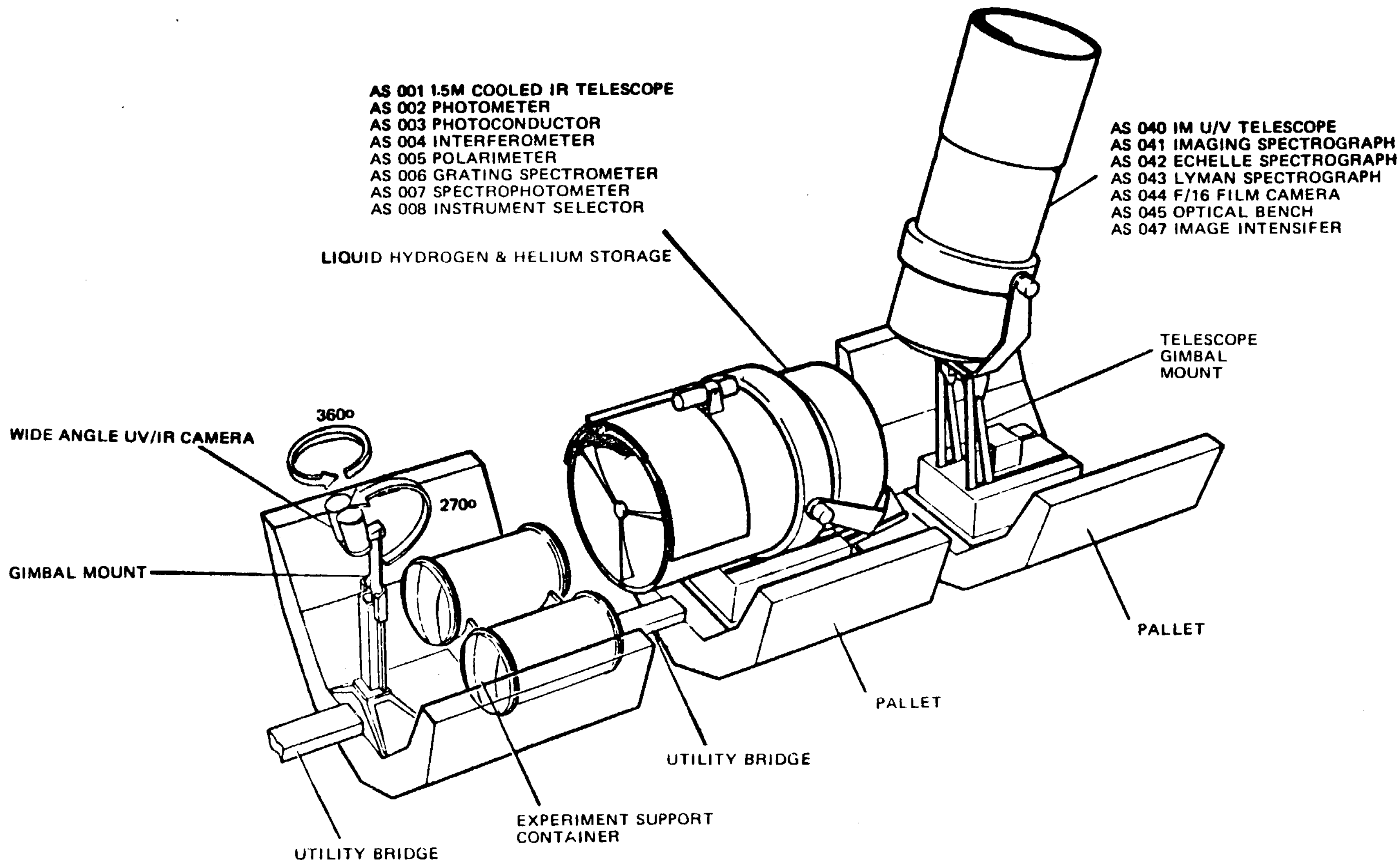


Figure 1-2 Astronomy Spacelab Payloads

During Phase A of this study a large sample of test data was used to place the statistical characteristics of the vibroacoustic environment on a meaningful basis. These characteristics are used in the development of the decision models.

From the above discussion, the need for this expanded study and the factors involved in it are evident. It brings together cost effectiveness studies using decision theory and statistical environmental characteristics obtained from a large data base to provide a realistic and less expensive approach to Shuttle Spacelab payload environmental test requirements. The scope of the proposed study is restricted to Spacelab facility type payloads but can readily be expanded to other payload configurations. Spacelab payloads are of particular interest because they are a major departure from current satellites since they are returned and because these payloads are planned for early STS flights. However, the results can not be arbitrarily generalized to include single mission payloads since the multiple mission use of facility type payloads is anticipated to have a significant effect on the costs.

The following sections of this volume present the results of the study and follow the general sequence in which the work was performed. Section 2 presents the statistical description of the environment during ground testing and flight. Similarly, Section 3 develops the statistical description of component dynamic strength including modifications of the strength distribution resulting from ground testing. Section 4 determines the test and flight failure probabilities determined from the statistical distributions of the environment and the component strength. Section 5 describes the decision model for evaluating the expected program cost corresponding to a selected test plan and develops the cost estimates for use in the decision model. The results of all the previous sections are used to evaluate the various test plans in Section 6. The conclusions and recommendations are given in Section 7.

SECTION 2

STATISTICAL REPRESENTATION OF THE ENVIRONMENT

The environment considered here is the vibration measured at the component mounting points as induced by the shuttle acoustic noise levels during flight or test. Previous studies and the analysis presented in Volume 2 have indicated that the component environment is best represented as a log normal distributed random variable which varies from flight to flight and with direction and location within the payload. The flight to flight variations are generally less than the variations with direction and location. In performing component tests, a discrete value of the environment is used. However, when tests are performed on the payload or on subassemblies, the variations due to direction and location will occur. Consequently, for payload or subassembly tests and for flight, the component environment will vary randomly while for component tests it will have a discrete value.

The component environment during flight is considered to be the product of two statistically independent variables. The first variable represents the intensity of the overall payload excitation and the second variable represents the effect of the spatial variations within the payload. Let $A(f)$ be a random variable representing the flight to flight variations in the payload acoustic excitation, $S(x)$ be a random variable reflecting the variations in the component environment due to location and direction, and $V(f,x)$ be a random variable representing the flight environment. Considering the component vibration environment to be a linear function of the excitation, we have the relation:

$$V(f,x) = A(f)\ S(x) \tag{2-1}$$

and

$$\log V(f,x) = \log A(f) + \log S(x) \tag{2-2}$$

Past studies have shown that a log normal distribution fits these variables. Therefore, Equation (2-2) provides a normal distribution of the logarithm of $V(f,x)$ as the sum of two normal distributions of the logarithms of $A(f)$ and $S(x)$. Using the Addition Theorem for the Normal Distribution, the mean, $\mathcal{M}$, and variance, $\mathcal{V}$, are related by the expressions:

$$\mathcal{M}\ \{\log V\} = \mathcal{M}\ \{\log A\} + \mathcal{M}\ \{\log S\} \tag{2-3}$$

$$\mathcal{V}\ \{\log V\} = \mathcal{V}\ \{\log A\} + \mathcal{V}\ \{\log S\} \tag{2-4}$$

since $A(f)$ and $S(x)$ are statistically independent. Therefore, if estimates of two distributions are obtained, then the distribution of the third can be determined.

The distribution of the component environment with direction and location has been developed under the Phase A portion of this study. The results of assembly level tests to a known acoustic test environment include the variations in the component environments due to position and location within the payload. This has been indicated by $S(x)$ in Equation (2-1).

The distribution of the excitation, $A(f)$, is estimated using acoustic measurements from a number of payload flights. The distribution of the flight environment is then estimated using Equations (2-3) and (2-4).

The shuttle environment obtained with the approach described above is presented in the following paragraphs of this section. First, the acoustic environment, $A(f)$, is estimated using the variance obtained from a series of Delta flight measurements in conjunction with current shuttle payload acoustic requirements. The Phase A results are then used to estimate the shuttle payload component environment, S(x), as a function of the acoustic level which also corresponds to a payload acoustic test environment. In the last paragraph, the component environment during shuttle flight is estimated by combining the acoustic and spatial distributions.

2.1 SHUTTLE ACOUSTIC ENVIRONMENT

In accordance with the NASA-GSFC philosophy, the 145 dB shuttle payload bay acoustic spectrum of the STS Payload Accommodations document is considered to represent the mean plus 2 sigma acoustic level, Reference 6. The shuttle payload acoustic environment is not well-defined and will depend on a number of factors such as the launch pad configuration, orbiter payload door structural configuration, door seal attenuation and the effects of vents. Current predictions vary from the 145 dB of the STS Payload Accommodations document. However to determine the component vibration levels, the acoustic excitation must be estimated for use in Equations (2-3) and (2-4). Therefore, it was assumed in this study that the payload bay acoustic level of 145 dB contained in Reference 6 would represent a 97.7 percentile environment. The spectrum shape is shown in Figure 2-1 and is used in this study.

Delta flight data was statistically analyzed to determine the flight to flight variation of the acoustic excitation at lift-off. Octave band sound pressure levels from a series of eight microphone measurements were obtained from NASA-GSFC and statistically analyzed using the GE STATPAC program to determine maximum liklihood estimates of the standard deviation. The analysis indicated that a normal distribution

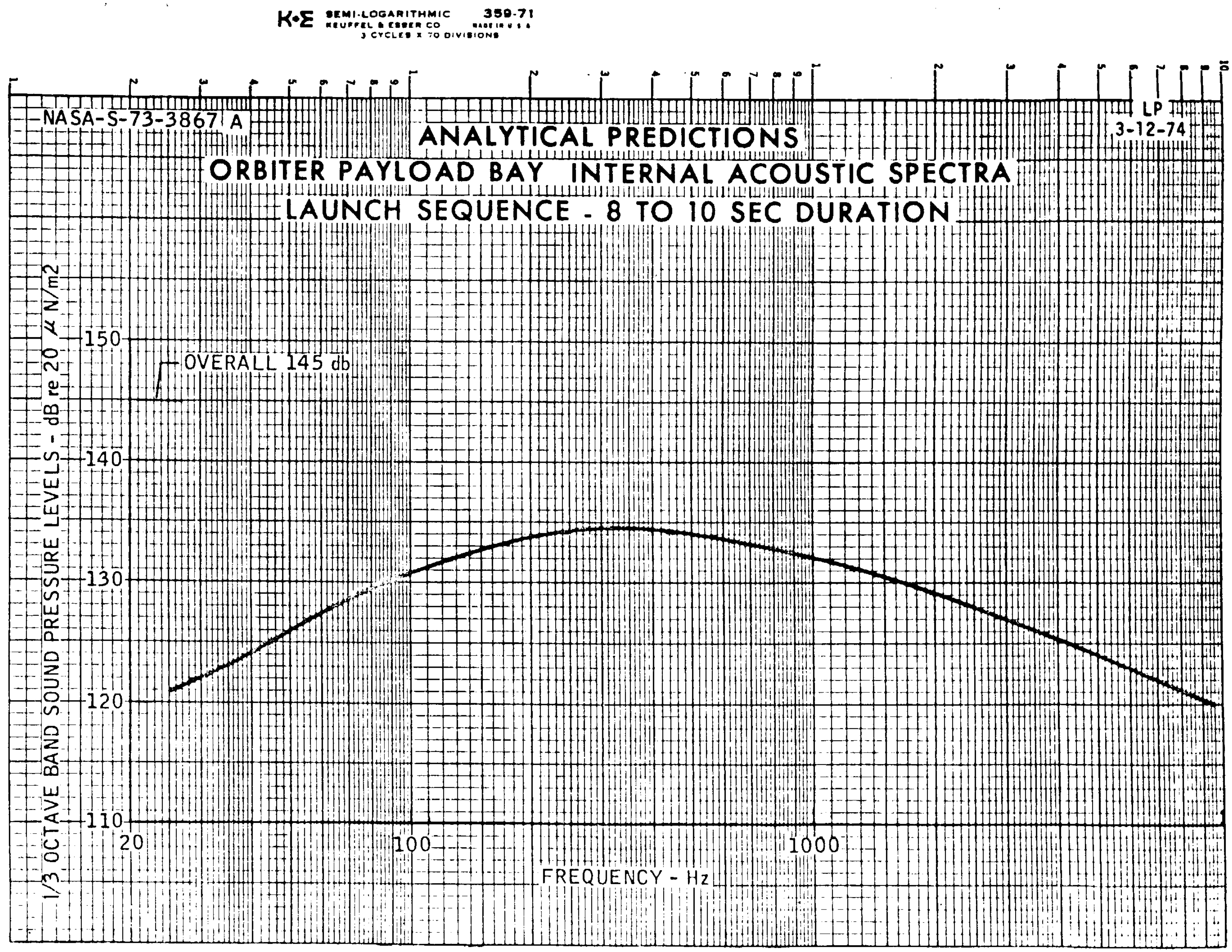


Figure 2-1 Shuttle Payload Bay Acoustic Spectrum (Source Ref: 6)

provided a good fit to the Sound Pressure Levels (dB), verifying that the pressure has a log normal distribution. The average standard deviation in the octave bands from 32 to 2000 Hz was found to be approximately 2 dB. This compares favorably with Titan III Transtage acoustic data which had a standard deviation of 1.7 dB during the lift-off condition, Reference 7. The Titan III data indicate that larger variations occur during flight, having a standard deviation of approximately 3 dB. However, because the maximum shuttle payload acoustic excitation is expected to occur at lift-off, the 2 dB estimate for the standard deviation is applicable.

In summary, the acoustic excitation for shuttle payloads is described as a log normal distributed random variable having a 2 sigma level and spectrum shape described by the 145 dB spectrum of the STS Payload Accommodations document and having a standard deviation of approximately 2 dB. This results in a 50 percentile level of approximately 141 dB and considers the variance of the octave bands to be constant. This defines the A(f) function to be used in Equations (2-3) and (2-4).

2.2 COMPONENT VIBRATION SPATIAL DISTRIBUTION

The spatial distribution of the component environment is obtained from the Phase A study results, modified to account for the acoustic spectrum shape of the shuttle payload environment. During the first phase of this study, the component vibration environment was determined for several zones within a spacecraft. Because most of the components are mounted in the Zone 3 section, the statistically derived vibration levels for this zone were used. The vibration levels are log normal distributed random variables. The reference acoustic excitation during Phase A corresponds to the test levels associated with the Delta launch vehicles and, therefore, the component vibration environment was modified for the acoustic spectrum shape predicted for shuttle payloads. The component PSD spectra for various percentiles were determined for the 145 dB acoustic spectrum and smoothed to determine component test requirements using the Random Response Spectrum approach described in Volume 2. Smoothed PSD test spectra at four probability levels are compared to extrapolated results in Figure 2-2 and the corresponding Random Response Spectra are shown in Figure 2-3 . The resulting RMS random vibration levels were then used to describe the spatial variation of the component vibration environment. The log normal vibration distribution for the 141 dB acoustic level has a median (50 percentile) value of 1.75 g RMS and a standard deviation of 10.9 dB.

It will be noted that these data consider a fixed acoustic excitation level and, therefore, contain only the variations in the environment due to spatial effects within the spacecraft. The data processed during Phase A were obtained from acoustic tests of spacecraft. The measured acoustic levels during each test were then used to normalize the vibration measurements to a reference acoustic excitation spectrum of 140 dB. Consequently, variations in the excitation have been eliminated to the extent possible leaving only the variation due to location and direction within the payload. This, then, defines the S(x) environmental function for use in Equations (2-3) and (2-4) for determination of the flight environment and also describes the component vibration environment during assembly test at a selected acoustic test level.

2.3 COMPONENT FLIGHT ENVIRONMENT

The component environment during flight is determined by combining the log normal excitation and spatial distributions. The 50 percentile component flight vibration environment is the 50 percentile environment for the 141 dB acoustic level, 1.75 g

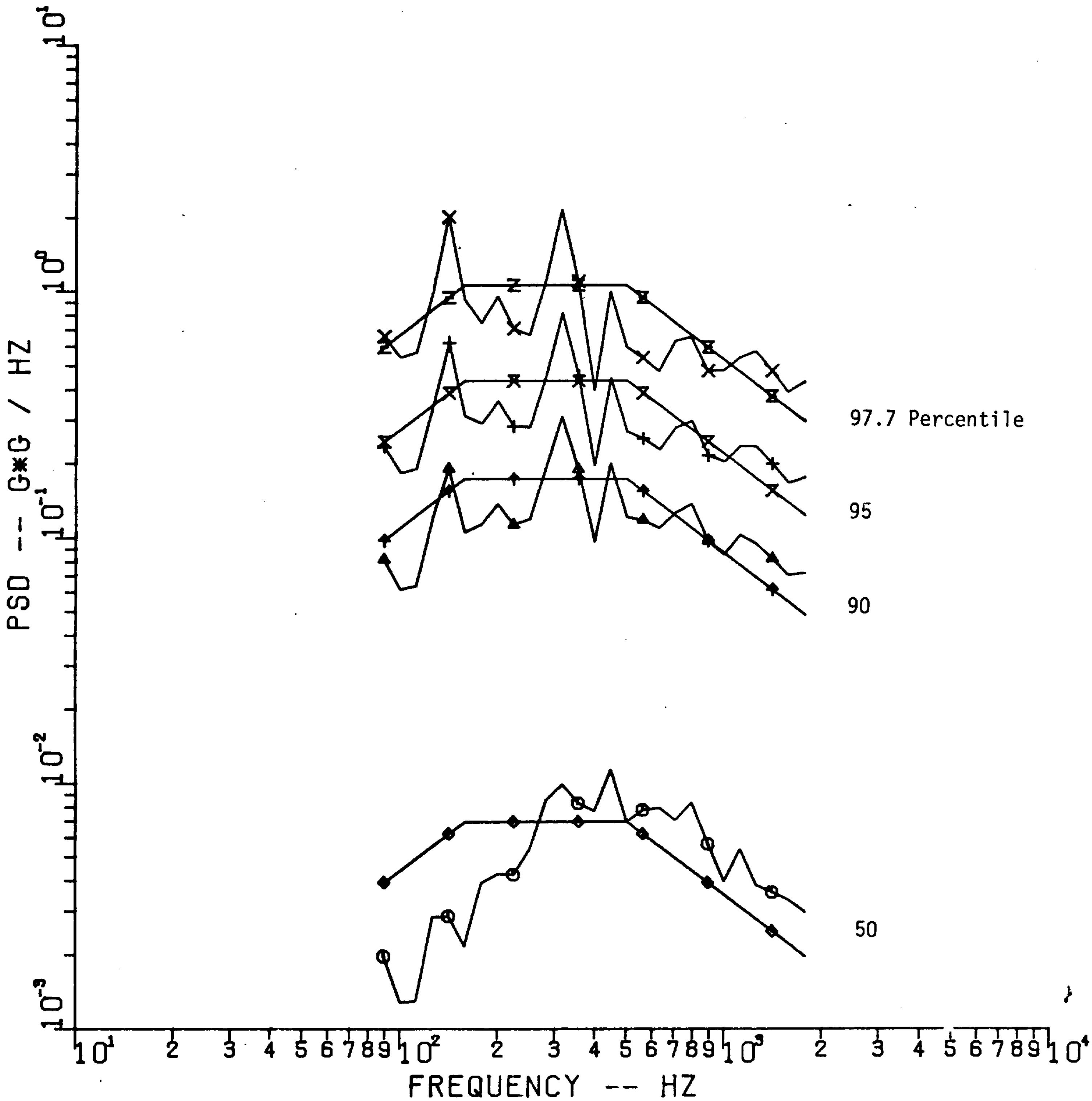


Figure 2-2 Test Spectra for 145 dB Shuttle Environment

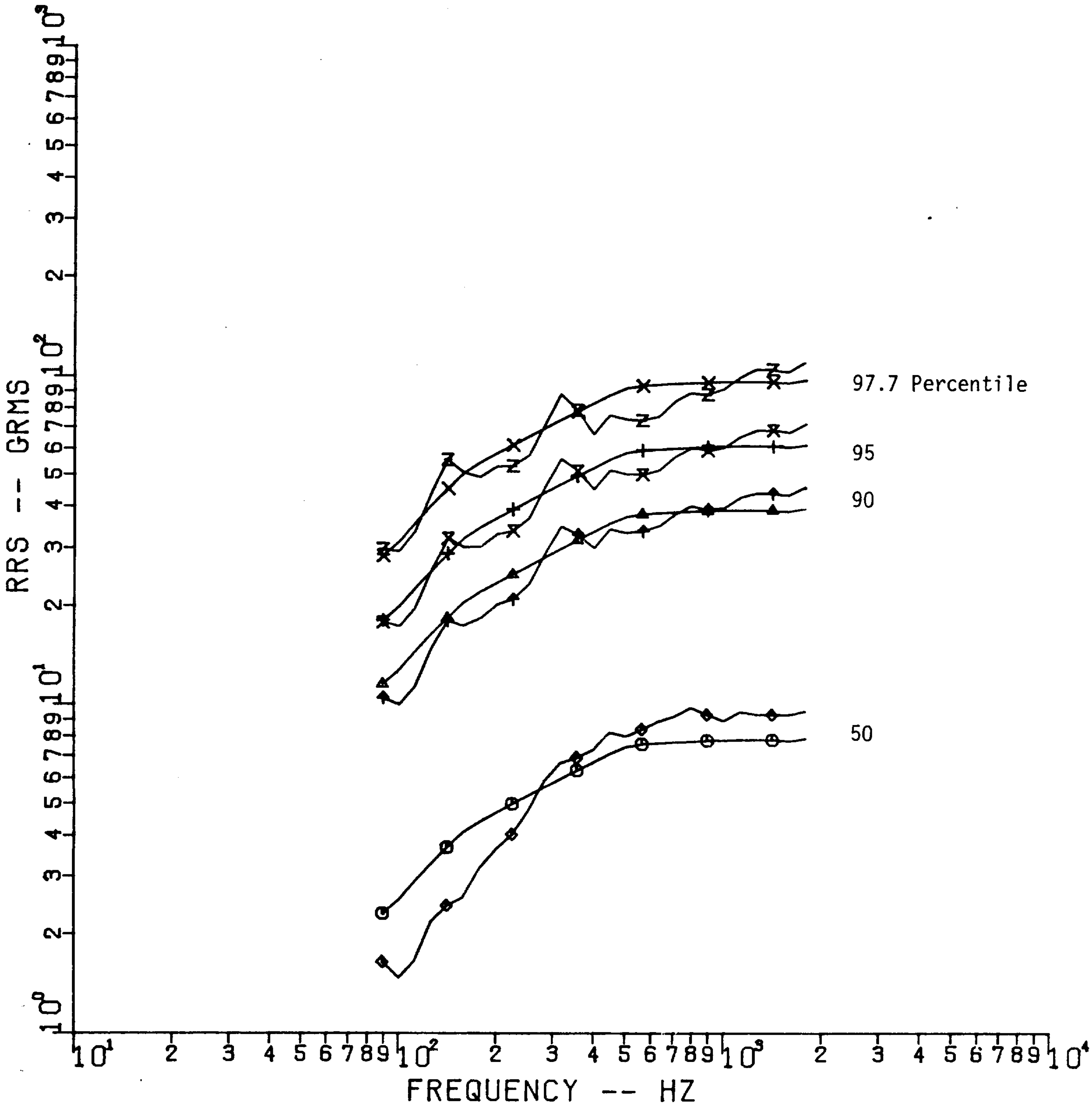


Figure 2-3 Random Response Spectra for 145 dB Shuttle Environment

RMS. The standard deviation is the combined standard deviations of the flight-to-flight and spatial distributions, the 2 dB and 10.9 dB, respectively. The standard deviation of the flight distribution is 11.1 dB ($[2^2 + 10.9^2]^{1/2}$) and is only slightly higher than the standard deviation of the spatial distribution.

The flight and assembly test distributions of the component vibroacoustic environment are shown in the cumulative probability plot of Figure 2-4. The assembly test environment is shown for several acoustic levels. Because the variance of the flight environment is approximately the same as the variance of the test environment, the slopes of the two distributions are nearly equal.

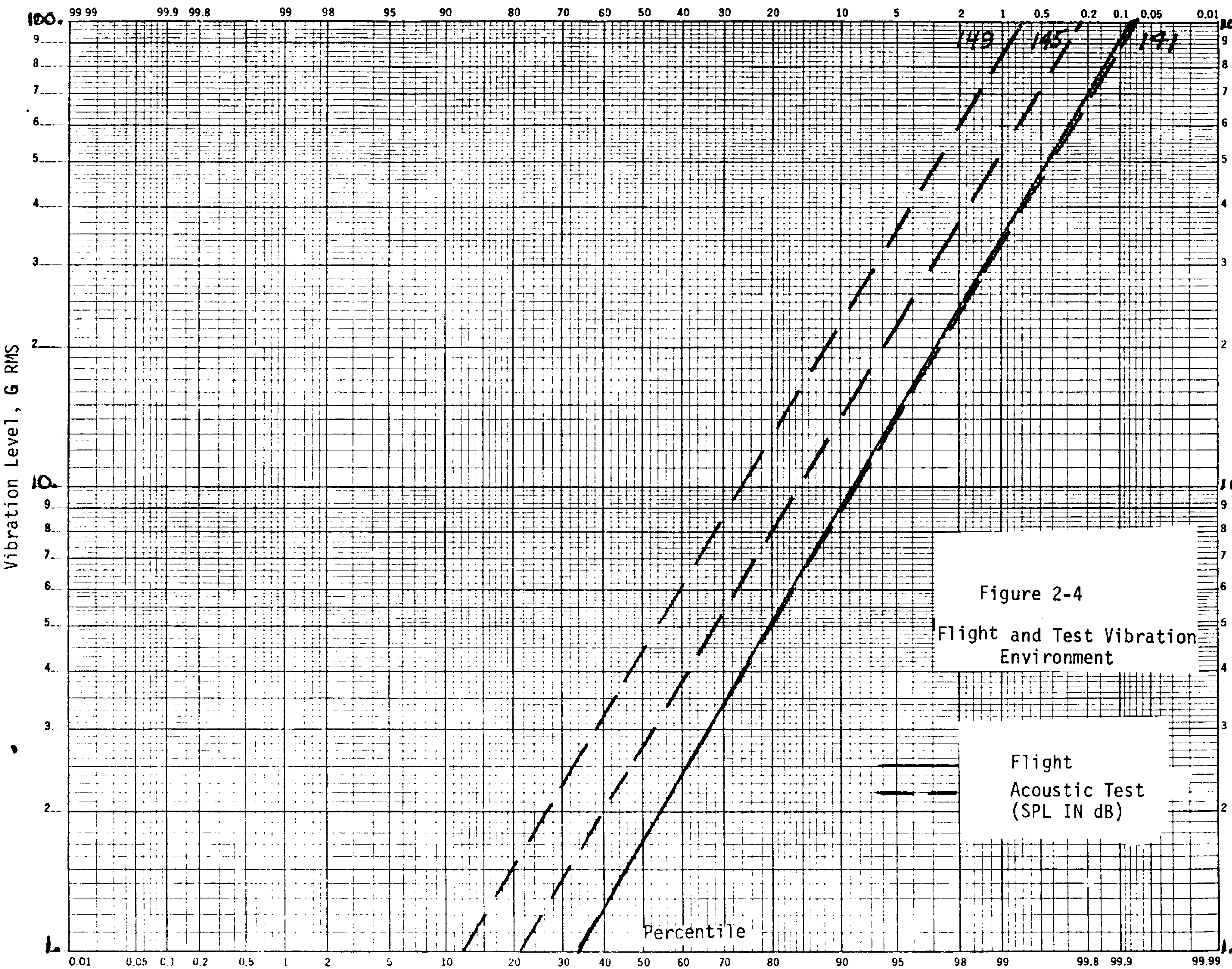


Figure 2-4

Flight and Test Vibration Environment

SECTION 3

STATISTICAL REPRESENTATION OF COMPONENT STRENGTH

The untested vibroacoustic strength of the components is treated as a log normal distributed random variable. In order to estimate the probability of failures occurring during ground testing and flight, the statistical distribution of the component strength is required. As a result of the tests performed prior to flight, the component designs are modified and strengthened to pass the prescribed tests. In addition, if the test components are flown, the component strength can actually be reduced as a result of testing. Consequently, the vibroacoustic strength distribution of the components is modified significantly by testing. The following paragraphs describe the estimated vibroacoustic strength of components as modified by tests at the component, subassembly and payload level. The initial discussion is similar to that presented in Volume 2, but is repeated here for continuity.

3.1 UNTESTED COMPONENT STRENGTH DISTRIBUTION

The untested component strength distribution is based on the results of previous studies by Stahle, References 2, 8 and 9 . In these studies, the results of component testing on nine spacecraft programs encompassing approximately 300 components were used to determine the proportion of components which pass the component vibration tests as a function of the test level. Subsequent to the studies, additional data were obtained from another program having a much higher level (25g RMS) and closely matched the projected number of component failures. The results are shown in Figure 3-1. It will be noted that a semilog graph is used so that the curve will satisfy the limiting condition of none passing the test when the vibration requirement becomes infinite.

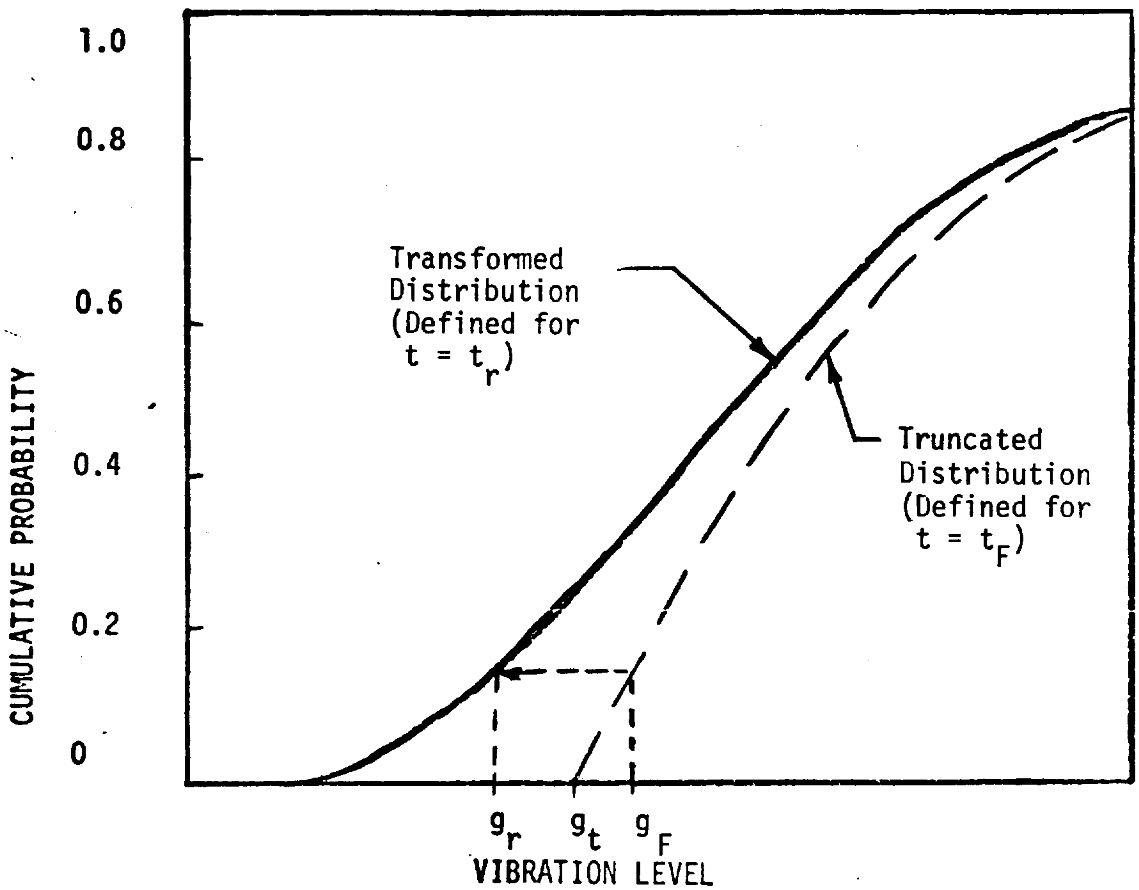


Figure 3-2 Truncated and Transformed Cumulative Strength Distributions for Components

If, however, protoflight components are used for subsequent assembly testing, the truncated strength distribution will not apply because of residual damage to the components. The strength distribution of such components that have been used for ground tests and are then subsequently used in assembly testing will have a transformed cumulative probability distribution that reflects the possibility of incipient failures occurring. One of the considerations that has been of major significance in the multiple use of components is the possibility of an incipient failure, i.e., the component has had a major part of its useful life expended as a result of testing. To account for this possibility it is necessary to determine the relation between the vibration level and the exposure time required to cause failure. For this study, the vibration level and the exposure time are considered to be related by:

$$\Sigma \, g^3 t = \text{Constant} \qquad (3\text{-}1)$$

where g is the RMS acceleration and t is the related exposure time. This relation considers the stress to be related to the vibration level (g) and the number of cycles to be related to the exposure duration (t). Reducing the vibration level by a factor of two extends the duration of the exposure that will cause equivalent damage by a factor of 8. Using Miner's Rule, the exposure at various vibration levels can be combined to determine the vibration level and duration which causes failure. This relation is in general agreement with the relation used for accelerated testing in Reference 10. Although the study of Edelberg, Reference 11, indicated that a g^2t relation may provide a better measure of damage, it is felt that the bulk of data test level, there is a definite probability of failure at small vibration levels due to those components having only a small amount of remaining strength after the component test has been performed. This transformed cumulative probability curve can be used to represent the component strength if protoflight components are used for subsequent assembly tests.

For this study, it was assumed that the assembly test time (t_r) and the component test time (t_t) were equal. Therefore Equation (3-4) reduced to

$$g_r = [g_F^3 - g_t^3]^{1/3} \qquad (3\text{-}5)$$

3.3 COMPONENT STRENGTH AFTER SUBASSEMBLY OR PAYLOAD TESTING

The component strength distribution after testing at higher assembly levels is determined from a stress-strength type of statistical analysis including a transformation to account for residual damage. In this study all tests of subassemblies or payloads are considered to be protoflight tests, i.e., the actual flight units are tested. Therefore, the g^3t transformation is applied to the post test component strength distribution for all test plans. In addition, following assembly level tests the strength distribution is redefined as a function of the acoustic intensity for evaluation of flight reliability. This is indicated conceptually in Figure 3-3 which indicates the changes to the cumulative probability distribution (CPD) of the component strength during assembly level testing. The modification of the component strength CPD is described below for each of the indicated steps.

The component strength CPD prior to assembly level testing and the component environment are indicated in Figure 3-3(a) as a function of the component vibration level. Two strength CPD curves are shown reflecting components which are prototype or protoflight.

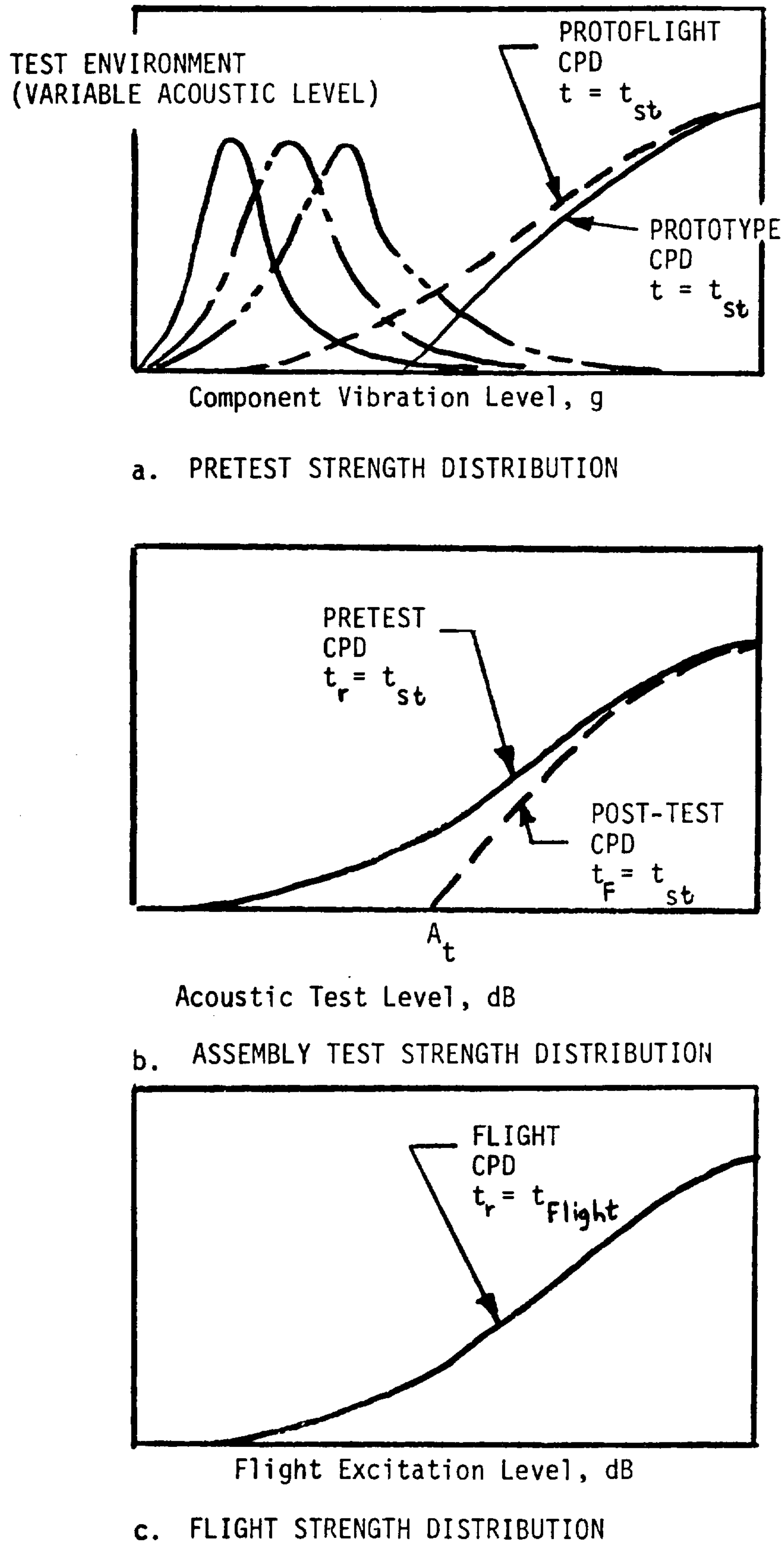


Figure 3-3 Effect of Assembly Testing on Component Strength Distribution

The prototype component strength CPD is truncated at the component test level since no previous high level tests have been performed on these units. The protoflight component CPD has been transformed as described in Section 3.2 for the assembly test duration (t_{st}) accounting for residual damage from component tests. The assembly level environment is treated as a log normal distributed random variable having the distribution of Zone 3 components developed in Volume 2 of this report. This distribution is considered to be the same for subassembly and payload level testing as well as flight, i.e., the test environment accurately simulates the flight environment at either assembly level. However, the distribution of the environment will be shifted as the acoustic intensity is changed as indicated in the figure and described in Section 2. For a selected test intensity, the probability of failure can be determined by doing a stress-strength statistical analysis. This can be repeated for various test intensities to describe the assembly test component strength CPD.

The component strength CPD before and after testing is shown in Figure 3-3(b). The pre-test CPD describes the probability of failures during assembly testing as a function of the acoustic level. As a result of the test at a selected level, marginal designs will fail so that the component strength CPD will be truncated at the selected acoustic test level, A_t. If similar components were subjected to the assembly level test at an acoustic level less than A_t, none would be expected to fail. This is indicated by the post test CPD. All of these curves are shown for an environmental duration of the assembly test, t_{st}. (It should be noted that there are two sets of CPD curves for Figure 3-3(b), one for prototype and one for protoflight components. Only one set is shown for clarity. This is also true for Figure 3-3(c)).

The effect of the test on the flight strength CPD is shown in Figure 3-3(c). Because the assembly test is performed on the flight components, the post test CPD must be transformed to account for residual damage. The transformation uses Equation (3-4) and accounts for both the acoustic test level used and the duration of the flight exposure. The truncated post test CPD of Figure 3-3(b) is transformed as indicated previously in Figure 3-2. In reality, there are a family of curves in Figure 3-3(c), each related to a particular assembly test level. Only one has been shown for clarity.

The exposure times used in the study are based on equal component and assembly test durations with the flight exposure being one half the test duration. Current practice uses component and assembly test durations which are on the order of 120 seconds. For the multiple mission payload considered in this study, the total duration of high level acoustic excitation during lift off will be approximately 120 seconds, i.e., 15 flights with high level durations of 8 seconds per flight. A flight duration of 60 seconds was selected to reflect an average flight value over the life of the payload. The transformation of the component CPD, therefore, reflects half the test duration.

The concepts described above are discussed in more detail in the Section 4 which presents the test and flight failure probabilities.

SECTION 4

TEST AND FLIGHT FAILURE PROBABILITIES

In this section, the probability of failures during testing and flight are determined for subsequent use in evaluating the cost effectiveness of the various test plans. During the tests, if a failure occurs, the component is redesigned and retested. To account for the test failure cost, both the probability of a failure occurring during the test and the probability of failures occurring during retesting must be considered. During flight, the failure of a component does not necessarily result in the loss of the payload because of the use of redundancy and because of possible parallel functions in the system. To properly define the consequence of flight failures, the probabilities of obtaining a partial success must also be considered. For the structure which is analyzed in considerable detail, the use of increased safety factors on the probability of structural failures must be considered. All of these failure probabilities are presented in this section.

The probability of a component vibroacoustic failure during test or flight is determined from a "stress-strength" analysis using the statistical distributions of the environment and the component strength. The equation for determining the probability that a failure will occur is

$$P_f = P\,\{\text{stress} > \text{strength}\} \tag{4-1}$$

$$P_f = 1 - \int_0^{\infty} \int_g^{\infty} g_{st}(g^*)\, g_{en}(g)\, dg^*\, dg \tag{4-2}$$

$$P_f = \int_0^{\infty} g_{en}(g)\, G_{st}(g)\, dg \tag{4-3}$$

where $G_{st}(g)$ is the cumulative probability of component strength as a function of vibration level and $g_{en}(g)$ is the probability density of the environmental "stress" as a function of vibration level. These distributions have been described in the previous sections. The transformation of the cumulative strength distribution for including residual damage effects has also been discussed. It will be noted that the CPD strength distribution is needed for the analysis rather than the probability density of the strength distribution. The probability of component failures is obtained from numerically integrating Equation (4-3) using the H6060 computer for the various distributions of interest.

The component failure probabilities during component testing, assembly testing and flight are described in the first six paragraphs of this section. Structural failures are then treated. The last paragraph formulates the probability of obtaining a portion of data from a flight in terms of the component vibration and structural reliabilities.

4.1 COMPONENT FAILURE PROBABILITIES DURING COMPONENT TESTING

The probability of a component failure during component testing is obtained directly from the component strength distribution for a selected component test requirement. The component test level is a deterministic quantity, i.e., the test level has a negligible statistical variation. Therefore, the probability of a component failure can be obtained directly from Figure 3-1. The component strength distribution as discussed earlier has been adjusted to match the relation shown in the figure. For this study, the component test level was varied from approximately the 88.5 percentile to the 99.9 percentile of the flight environment using the distribution given in Figure 2-4. This is considered to cover the range of values of practical interest. A total of ten component test levels were used to describe the effect of varying the component test level and have test failure probabilities given in Table 4-1.

Table 4-1

Component Failure Probability During Component Test

Component Test Level		Probability of Failure
g (RMS)	U_v	
8.1	1.2	0.15919
13.5	1.6	0.24625
22.6	2.0	0.37321
29.3	2.2	0.45326
37.7	2.4	0.53909
48.5	2.6	0.62960
62.7	2.8	0.72199
80.9	3.0	0.80775
104.4	3.2	0.88083
134.8	3.4	0.93556

The failure probabilities are given for values of the standardized variable of the flight vibration environment, U_v (i.e. a value of 2 represents the 2 sigma or 97.7 percentile and a value of zero represents the mean) and the associated RMS g levels.

Provisions for multiple tests of a component were included using Pascal's distribution, Reference 12. To provide a realistic model, it is not practical to assume that after a component fails the initial test, it will pass the next test. This is particularly true if high component test levels are specified. Using the special case of Pascal's distribution for the single occurrence of the event U in exactly x trials, we can estimate the probability that x tests will be required for a component to pass. This can be written as:

$$p\{x\} = (1 - \theta)^{x-1}\,\theta \qquad (4\text{-}4)$$

where θ = probability of a component passing the test

x = number of tests

For example, if the probability of a component passing a test is 0.9, then the following probabilities result for multiple tests:

x	p{x}	P{x}
1	0.9	.9
2	0.09	.99
3	0.009	.999
4	0.0009	.9999
5	0.00009	.99999

where P{x} is the cumulative probability of requiring x tests for the component to pass.

Therefore, it is unlikely that the component will require more than one retest to pass, i.e., only one component in a hundred would require more than one retest. However, consider a severe test requirement which results in a 50 percent probability of a component passing the test. Now, the following values are calculated:

x	p{x}	P{x}
1	0.5	0.5
2	0.25	0.75
3	0.125	0.875
4	0.0625	0.9375
5	0.03125	0.96875

With the more severe test, there is a 25 percent probability that it will not pass the retest and a 12.5 percent probability that it will require more than two retests. This appears to provide a more realistic model of component testing than assuming it will always pass the retest. The assumption is that the test observations are stochastically independent. This can be interpreted to mean that the component redesign overcomes the deficiency exposed during the previous test with a probability of passing equal to that of the original component designs. This relation for estimating the number of retests required appears to provide a reasonable estimate.

4.2 COMPONENT FAILURE PROBABILITIES DURING PAYLOAD TESTING

The probability of a component failing during payload testing is determined using the applicable component strength distribution and the payload vibroacoustic response distribution in a stress-strength statistical analysis. The payload response distribution is described in Section 2.2 and is shifted as the acoustic level is changed, The payload acoustic test level is varied from 141 dB to 155 dB to cover the range of interest. Several component strength distributions are considered for the various test plans:

1. Untested Components - For Test Plan 5, the component strength distribution is defined as a function of the vibration level as described in Section 3.1. Although no component testing is required, the component strength is considered to increase as the component design requirement is increased. There is no difference in the strength of prototype or protoflight components since neither have been previously tested.

2. Prototype Components - For Test Plan 3, the prototype component strength distribution is truncated at the component vibration level. This reflects the use of new components during the test of the same design as those which have passed the component payload test.

3. Protoflight Components - For Test Plan 3, the protoflight component strength distribution is obtained from the truncated prototype strength distribution by applying the g^3t transformation of Equation (3-4) with a time ratio of one.

The resulting probabilities are given in Table 4-2 for each of the three types of components for 10 component vibration levels and eight payload test levels. The values are the component reliabilities during payload testing, i.e., one minus the probability of a component failing during payload testing.

Table 4-2

Component Vibroacoustic Reliabilities During Payload Testing

UnTested Components

Payload Test Level (dB)

Component Test Level g (RMS)	141	143	145	147	149	151	153	155	157
8.1	9.3202E-01	9.0654E-01	8.7461E-01	8.3576E-01	7.8986E-01	7.3719E-01	6.7848E-01	6.1493E-01	5.4814E-01
13.5	9.6075E-01	9.4388E-01	9.2175E-01	8.9355E-01	8.5368E-01	8.1677E-01	7.6788E-01	7.1248E-01	6.5151E-01
22.6	9.7796E-01	9.6726E-01	9.5260E-01	9.3311E-01	9.0723E-01	8.7633E-01	8.3784E-01	7.9228E-01	7.3993E-01
29.3	9.8559E-01	9.7515E-01	9.6337E-01	9.4738E-01	9.2528E-01	8.9927E-01	8.6567E-01	8.2509E-01	7.7747E-01
37.7	9.8761E-01	9.8093E-01	9.7141E-01	9.5824E-01	9.4054E-01	9.1745E-01	8.8817E-01	8.5213E-01	8.0904E-01
49.5	9.9057E-01	9.8526E-01	9.7755E-01	9.6669E-01	9.5184E-01	9.3212E-01	9.0667E-01	8.7477E-01	8.3597E-01
62.7	9.9279E-01	9.8855E-01	9.8230E-01	9.7334E-01	9.6088E-01	9.4406E-01	9.2198E-01	8.9385E-01	8.5904E-01
80.9	9.9439E-01	9.9097E-01	9.8584E-01	9.7838E-01	9.6785E-01	9.5340E-01	9.3416E-01	9.0927E-01	8.7800E-01
104.4	9.9555E-01	9.9274E-01	9.8847E-01	9.8218E-01	9.7317E-01	9.6066E-01	9.4376E-01	9.2159E-01	8.9337E-01
134.8	9.9636E-01	9.9400E-01	9.9037E-01	9.8496E-01	9.7713E-01	9.6611E-01	9.5106E-01	9.3109E-01	9.0536E-01

Prototype Components

Component Test Level g (RMS)	141	143	145	147	149	151	153	155	157
8.1	9.4893E-01	9.2757E-01	8.9998E-01	8.6545E-01	8.2354E-01	7.7425E-01	7.1804E-01	6.5590E-01	5.8928E-01
13.5	9.7576E-01	9.6369E-01	9.4709E-01	9.2501E-01	8.9652E-01	8.6094E-01	8.1785E-01	7.6732E-01	7.0987E-01
22.6	9.8988E-01	9.8392E-01	9.7520E-01	9.6282E-01	9.4580E-01	9.2315E-01	8.9396E-01	8.5753E-01	8.1349E-01
29.3	9.9381E-01	9.8987E-01	9.8389E-01	9.7512E-01	9.6267E-01	9.4554E-01	9.2274E-01	8.9334E-01	8.5664E-01
37.7	9.9628E-01	9.9373E-01	9.8973E-01	9.8366E-01	9.7477E-01	9.6213E-01	9.4476E-01	9.2164E-01	8.9186E-01
49.5	9.9784E-01	9.9624E-01	9.9365E-01	9.8959E-01	9.8344E-01	9.7442E-01	9.6161E-01	9.4401E-01	9.2059E-01
62.7	9.9880E-01	9.9784E-01	9.9624E-01	9.9365E-01	9.8958E-01	9.8341E-01	9.7435E-01	9.6147E-01	9.4377E-01
80.9	9.9935E-01	9.9880E-01	9.9785E-01	9.9625E-01	9.9365E-01	9.8958E-01	9.8340E-01	9.7431E-01	9.6139E-01
104.4	9.9967E-01	9.9936E-01	9.9882E-01	9.9787E-01	9.9628E-01	9.9370E-01	9.8964E-01	9.8348E-01	9.7440E-01
134.8	9.9983E-01	9.9967E-01	9.9937E-01	9.9883E-01	9.9789E-01	9.9632E-01	9.9375E-01	9.8972E-01	9.8358E-01

Protoflight Components

Component Test Level g (RMS)	141	143	145	147	149	151	153	155	157
8.1	9.2845E-01	9.0288E-01	8.7107E-01	8.3259E-01	7.8728E-01	7.3541E-01	6.7767E-01	6.1517E-01	5.4942E-01
13.5	9.5945E-01	9.4284E-01	9.2119E-01	8.9376E-01	8.5992E-01	8.1932E-01	7.7193E-01	7.1813E-01	6.5875E-01
22.6	9.7852E-01	9.6854E-01	9.5492E-01	9.3685E-01	9.1350E-01	8.8415E-01	8.4823E-01	8.0547E-01	7.5598E-01
29.3	9.8483E-01	9.7733E-01	9.6687E-01	9.5267E-01	9.3389E-01	9.0972E-01	8.7943E-01	8.4250E-01	7.9872E-01
37.7	9.8934E-01	9.8377E-01	9.7582E-01	9.6479E-01	9.4987E-01	9.3022E-01	9.0504E-01	8.7362E-01	8.3548E-01
48.5	9.9263E-01	9.8856E-01	9.8263E-01	9.7421E-01	9.6258E-01	9.4690E-01	9.2635E-01	9.0011E-01	8.6752E-01
62.7	9.9503E-01	9.9213E-01	9.8782E-01	9.8156E-01	9.7271E-01	9.6051E-01	9.4414E-01	9.2275E-01	8.9554E-01
80.9	9.9670E-01	9.9468E-01	9.9161E-01	9.8705E-01	9.8045E-01	9.7114E-01	9.5836E-01	9.4127E-01	9.1902E-01
104.4	9.9786E-01	9.9648E-01	9.9434E-01	9.9109E-01	9.8628E-01	9.7934E-01	9.6959E-01	9.5624E-01	9.3845E-01
134.5	9.9864E-01	9.9771E-01	9.9625E-01	9.9397E-01	9.9054E-01	9.8547E-01	9.7819E-01	9.6798E-01	9.5404E-01

The probability of having multiple component failures during payload testing is determined from the binomial distribution. The probability of i failures occurring is:

$$P_{st}\{i\} = \frac{n!}{(i)!\,(n-i)!} (p_{stf})^{i} (1 - p_{stf})^{n-i} \qquad (4\text{-}5)$$

where p_{stf} is the probability of an individual component failing during payload testing and n is the number of components in the payload. This assumes that the component failures are stochastically independent and represents the probability of having exactly i failures. The component failure probability, p_{stf}, is obtained from Table 4-2.

When multiple failures occur, the number of retests required must be determined. The general Pascal distribution was used, Reference 12. This defines the probability of obtaining "a" events having a probability θ in x trials as

$$P\{X\} = \left(\frac{\theta}{1 - \theta}\right)^{a} \frac{(x-1)!}{(a-1)!\,(x-a)!} (1-\theta)^{x} \qquad (4\text{-}6)$$

where $x \geq a$

For this application it is the probability that x retests will be required for "a" components to pass the test where θ is the probability of a component successfully passing a test. This is a generalization of the special Pascal distribution used in Section 4.1 for the component retest probability where "a" equals 1.

4.3 COMPONENT FAILURE PROBABILITIES DURING SUBASSEMBLY TESTING

The probabilities of component failures during subassembly testing are considered to be the same as during payload testing. In this study it is assumed that the subassembly test provides an accurate simulation of the payload environment. Therefore, the component environment distribution will be the same as it was for payload testing. The failure probabilities are the same as those given in Section 4.2.

4.4 COMPONENT FLIGHT FAILURE PROBABILITIES AFTER COMPONENT TESTING

For Test Plan 1, the probability of a component failing during flight after successfully passing a component test is required. This is obtained from a stress-strength statistical analysis. The environmental distribution is that of flight described in Section 2.3 and is broader than the acoustic test environment. Two component strength distributions are used. For prototype components a strength distribution truncated at the component test level is used. For protoflight components, the truncated prototype strength distribution is transformed using the g^3t relation. The resulting component vibroacoustic reliabilities were determined for 10 component test levels and are given in Table 4-3.

4.5 COMPONENT FLIGHT FAILURE PROBABILITIES AFTER ASSEMBLY LEVEL TESTING

The probability of a component flight failure after assembly level testing was determined from a stress-strength statistical analysis using the component strength distribution as a function of the acoustic test level and the flight distribution of the acoustic level. The probability of a component failure was determined for eight acoustic levels during payload testing (Section 4.2, Table 4-2). For a selected value of the acoustic test level, the component strength distribution is first truncated at that acoustic level and then transformed using the g^3t relation to obtain the flight strength distribution. The g^3t relation of Equation (3-4) was used with a flight time (t_r) equal to half the test time (t_t). Component strength distributions were determined in this manner for assembly acoustic test levels of 141, 143, 145, 147, 149, 151, 153 and 155 dB. The component flight failure probabilities were then

TABLE 4-3

Component Flight Vibroacoustic Reliabilities After Component Testing

Component Test Level		Prototype	Protoflight
g (RMS)	U_v		
8.1	1.2	0.94686	0.92640
13.5	1.6	0.97429	0.95780
22.6	2.0	0.98900	0.97735
29.3	2.2	0.99319	0.98387
37.7	2.4	0.99585	0.98858
48.5	2.6	0.99754	0.99204
62.7	2.8	0.99861	0.99458
80.9	3.0	0.99924	0.99637
104.4	3.2	0.99960	0.99762
134.8	3.4	0.99980	0.99847

determined by integrating the flight acoustic distribution and cumulative strength distribution curves numerically. The procedure was repeated for component strength distributions corresponding to:

1. Components which had been protoflight tested at the assembly level (TP4,5).
2. Components which were prototype tested at the component level and were also protoflight tested at the assembly level (TP2,3).
3. Components which were protoflight tested at both the component level and the assembly level (TP2, 3).

The resulting component vibroacoustic reliabilities are given in Table 4-4.

The probability of multiple flight failures is defined by the binomial distribution in the same manner as discussed in Section 4.2 for payload testing using the applicable probabilities from Table 4-4.

4.6 PROBABILITIES OF STRUCTURAL FAILURES

Unlike component vibration strength, the strength of the primary structure is considered to be influenced significantly by the selection of a design safety factor. Detailed analysis of components is generally not performed in sufficient depth to assure the vibration adequacy with regard to structural and piece-part integrity. Primary structure, on the other hand, is rigorously analyzed and will have a significantly greater load carrying capability if higher safety factors are used. In this portion of the study, emphasis is placed on the primary structure load carrying ability and uses the results of the study by Thomas and Hanagud, Reference 3. These results should be restricted to consideration of primary structure integrity. No attempt is made to account for secondary structure problems such as resonant coupling which are often encountered during spacecraft vibration testing.

Table 4-4

Component Vibroacoustic Reliability After Assembly Level Testing

Protoflight At Assembly Level
Assembly Test Level (dB)

Component Test Level g rms	141	143	145	147	149	151	153	155
8.1	9,8212E-01	9,8730E-01	9,9147E-01	9,9453E-01	9,9660E-01	9,9795E-01	9,9878E-01	9,9929E-01
13.5	9,8846E-01	9,9154E-01	9,9413E-01	9,9611E-01	9,9751E-01	9,9846E-01	9,9906E-01	9,9944E-01
22.6	9,9278E-01	9,9453E-01	9,9607E-01	9,9731E-01	9,9823E-01	9,9887E-01	9,9929E-01	9,9957E-01
29.3	9,9434E-01	9,9563E-01	9,9681E-01	9,9776E-01	9,9851E-01	9,9904E-01	9,9939E-01	9,9962E-01
37.7	9,9552E-01	9,9649E-01	9,9740E-01	9,9816E-01	9,9875E-01	9,9918E-01	9,9947E-01	9,9967E-01
48.5	9,9644E-01	9,9717E-01	9,9787E-01	9,9847E-01	9,9894E-01	9,9930E-01	9,9954E-01	9,9971E-01
62.7	9,9716E-01	9,9771E-01	9,9825E-01	9,9872E-01	9,9911E-01	9,9940E-01	9,9960E-01	9,9974E-01
80.9	9,9770E-01	9,9813E-01	9,9855E-01	9,9893E-01	9,9924E-01	9,9948E-01	9,9965E-01	9,9977E-01
104.4	9,9812E-01	9,9844E-01	9,9878E-01	9,9909E-01	9,9934E-01	9,9955E-01	9,9969E-01	9,9980E-01
134.8	9,9842E-01	9,9868E-01	9,9895E-01	9,9921E-01	9,9943E-01	9,9960E-01	9,9973E-01	9,9982E-01

Prototype At Component Level, Protoflight At Assembly Level

	141	143	145	147	149	151	153	155
8.1	9,8524E-01	9,8927E-01	9,9263E-01	9,9517E-01	9,9695E-01	9,9813E-01	9,9887E-01	9,9934E-01
13.5	9,9183E-01	9,9378E-01	9,9552E-01	9,9693E-01	9,9798E-01	9,9871E-01	9,9920E-01	9,9951E-01
22.6	9,9600E-01	9,9679E-01	9,9756E-01	9,9824E-01	9,9878E-01	9,9918E-01	9,9947E-01	9,9966E-01
29.3	9,9735E-01	9,9781E-01	9,9829E-01	9,9873E-01	9,9909E-01	9,9938E-01	9,9959E-01	9,9973E-01
37.7	9,9828E-01	9,9854E-01	9,9882E-01	9,9910E-01	9,9934E-01	9,9953E-01	9,9968E-01	9,9979E-01
48.5	9,9892E-01	9,9906E-01	9,9922E-01	9,9938E-01	9,9953E-01	9,9966E-01	9,9976E-01	9,9984E-01
62.7	9,9935E-01	9,9942E-01	9,9950E-01	9,9959E-01	9,9968E-01	9,9976E-01	9,9983E-01	9,9988E-01
80.8	9,9963E-01	9,9965E-01	9,9969E-01	9,9974E-01	9,9979E-01	9,9984E-01	9,9988E-01	9,9991E-01
104.4	9,9979E-01	9,9980E-01	9,9982E-01	9,9984E-01	9,9987E-01	9,9989E-01	9,9992E-01	9,9994E-01
134.8	9,9989E-01	9,9989E-01	9,9990E-01	9,9991E-01	9,9992E-01	9,9993E-01	9,9995E-01	9,9996E-01

Protoflight At Component Level, Protoflight At Assembly Level

	141	143	145	147	149	151	153	155
8.1	9,8200E-01	9,8730E-01	9,9152E-01	9,9458E-01	9,9664E-01	9,9797E-01	9,9880E-01	9,9930E-01
13.5	9,8863E-01	9,9172E-01	9,9428E-01	9,9623E-01	9,9759E-01	9,9851E-01	9,9909E-01	9,9946E-01
22.6	9,9327E-01	9,9492E-01	9,9637E-01	9,9752E-01	9,9836E-01	9,9895E-01	9,9934E-01	9,9960E-01
29.3	9,9497E-01	9,9613E-01	9,9718E-01	9,9803E-01	9,9868E-01	9,9914E-01	9,9945E-01	9,9966E-01
37.7	9,9627E-01	9,9708E-01	9,9783E-01	9,9846E-01	9,9895E-01	9,9930E-01	9,9955E-01	9,9971E-01
48.5	9,9728E-01	9,9783E-01	9,9835E-01	9,9881E-01	9,9917E-01	9,9944E-01	9,9963E-01	9,9976E-01
62.7	9,9806E-01	9,9843E-01	9,9878E-01	9,9910E-01	9,9936E-01	9,9956E-01	9,9970E-01	9,9981E-01
80.3	9,9865E-01	9,9888E-01	9,9912E-01	9,9933E-01	9,9952E-01	9,9966E-01	9,9977E-01	9,9984E-01
104.4	9,9907E-01	9,9922E-01	9,9937E-01	9,9952E-01	9,9964E-01	9,9974E-01	9,9982E-01	9,9988E-01
134.8	9,9938E-01	9,9947E-01	9,9956E-01	9,9965E-01	9,9974E-01	9,9981E-01	9,9986E-01	9,9991E-01

Three design options were considered for the primary structure. In Test Plan 1, no structural test was considered but a design safety factor of 2 was used to assure a high structural reliability. In Test Plans 1A and 3A, a prototype structure (SDM) was tested and a design safety factor of 1.25 was used in accordance with current spacecraft design practice. In the remaining test plans, a protoflight structural test was used with a design safety factor of 1.5 to minimize the probability of failing the flight structure during testing.

The statistical distribution of the load was considered to be normal having a coefficient of variation of 0.129. In Thomas' study analyses were performed for various statistical distributions of the load having coefficients of variation ranging from 0.058 to 0.37. The coefficient of variation is defined as the ratio of the standard deviation to the mean. Large values of the coefficient of variation reflect distributions having a relatively large variance compared to the mean. A review of current launch vehicle data indicated that a value of approximately 0.1 was representative. Consequently, a coefficient of variation of 0.129 for which results were available was selected.

The strength distribution of Thomas, based on the statistical analysis of structural test results of Saturn V, was used. It is felt that these data are representative of current state-of-the-art design practices. The data are for tests of fifty structural assemblies and have been analyzed by Thomas in his study. The resulting strength distribution prior to testing was defined as a Weibull distribution using maximum likelihood estimates of the parameters.

The resulting flight reliabilities for the structure were taken directly from Thomas' study and are shown in Table 4-5. Although no structural test is performed with Test Plan 1, the design safety factor of 2 provides a highly reliable structure. The test of

Table 4-5

Structure Reliability During Flight

Test Plan	Safety Factor	Flight Reliability	Remarks
1	2.0	0.99927	No structural test
1A	1.25	0.99875	Prototype only
2	1.5	0.999997	Protoflight only
3	1.5	0.999997	Protoflight as part of payload test
3A	1.25	0.99875	Prototype only
4	1.5	0.999997	Protoflight only
5	1.5	0.999997	Protoflight only

the actual structure to limit load in combination with a design safety factor of 1.5 results in the most reliable structure with Test Plans 2, 4 and 5. The combination of prototype structural testing with a safety factor of 1.25 results in the lightest weight but least reliable structure for Test Plans 1A and 3A.

The probabilities of failures during testing were also taken directly from Thomas' study. A failure probability of 0.34 or 0.04 was used for prototype structural testing (1.25 safety factor) or protoflight structural testing (1.5 safety factor), respectively.

4.7 PROBABILITY OF MISSION LOSS

The probability of achieving the flight objectives is needed to determine the cost of flight failures. In the previous paragraphs, the probability of a component failure during flight was determined. However, a component flight failure does not generally result in a complete loss of the payload. To determine the expected cost of a flight failure, a reliability model at the component level is needed to estimate the probability of achieving a portion of the flight objectives.

The payload reliability model shown in Figure 4-1 is used to estimate the probability of achieving the flight objectives. The model represents the payload system as a series of redundant components and a group of parallel experiments. The series components represent the basic subsystems used for housekeeping functions and are

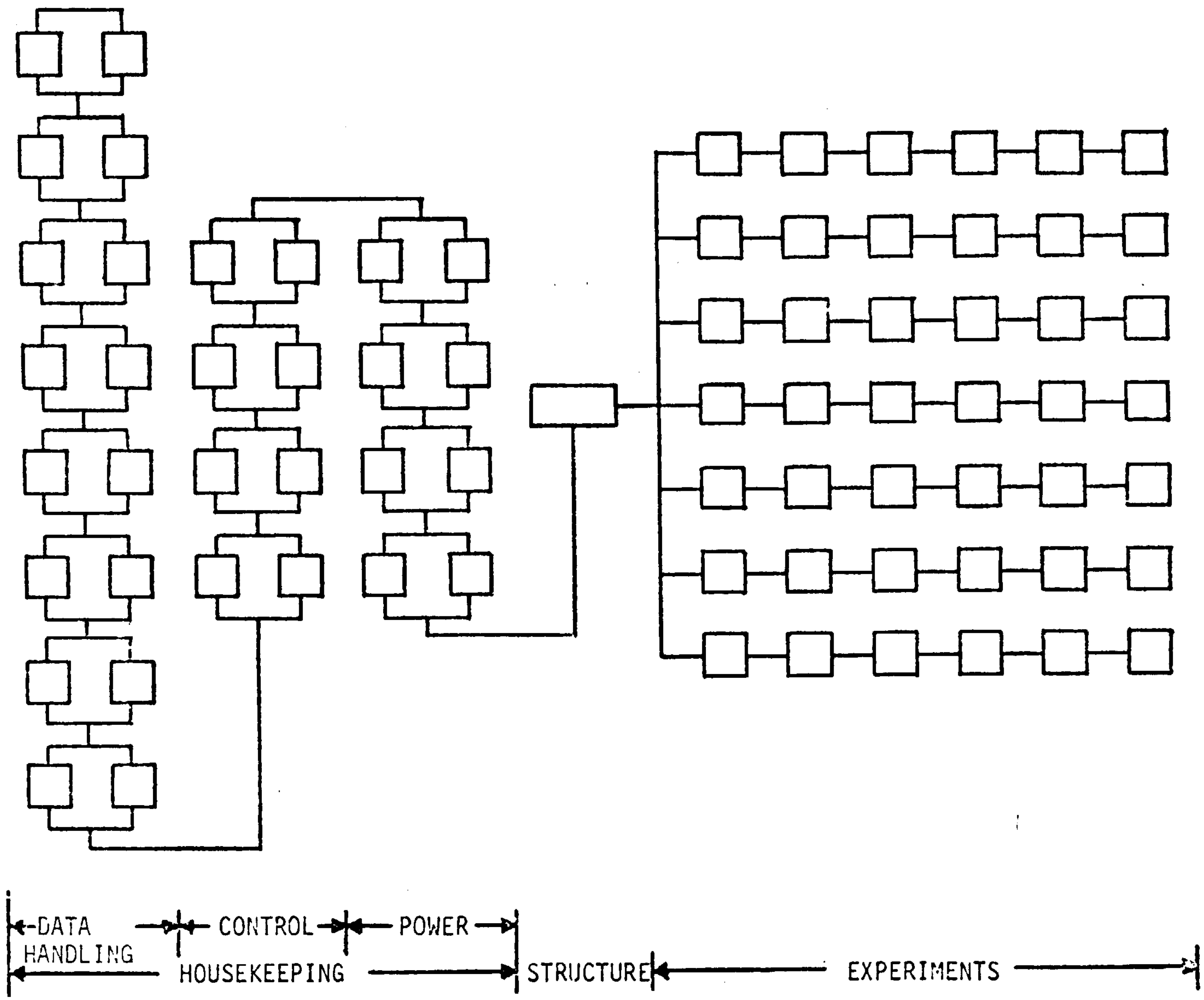


Figure 4-1 Payload Reliability Model

assumed to have single redundancy, except for the structure. These components are essential to the success of the flight. Each experiment is composed of a number of series components and does not include any redundancy. Parameters of the model are the following:

NEXP = number of parallel experiments
NCPE = number of components within an experiment
NCCE = number of redundant series components including the structure

Representative values for these parameters used in this study are:

NEXP = 1 and 7
NCPE = 2 and 6
NCCE = 17 (including the structure)

Using this payload reliability model, the probability of obtaining data from a portion of the experiments can now be estimated.

The probability of losing data from one or more experiments is estimated for use in determining the cost of flight failures. For the payload model of Figure 4-1, the possible outcomes from a flight are the loss of data from 0 to NEXP experiments. The probability of losing data from i experiments, P_i, can be formulated in terms of the vibroacoustic reliabilities of the components as follows:

$$P_0 = \left\{\prod_{1}^{NCCE}(R_C)_i\right\}\left\{\prod_{1}^{NEXP}(R_E)_i\right\} \tag{4-7}$$

$$P_n = \left\{\prod_{1}^{NCCE}(R_C)_i\right\}B_n \qquad n = 1, 2 \ldots, (NEXP-1) \tag{4-8}$$

$$P_{NEXP} = \left[1 - \left\{\prod_{1}^{NCEE}(R_C)_i\right\}\right]\left\{\sum_{n=0}^{NEXP} B_n\right\} + \left\{\prod_{1}^{NCEE}(R_C)_i\right\}B_{NEXP} \tag{4-9}$$

where

$$B_n = \frac{NEXP\,!}{n\,!\,(NEXP-n)!} \quad (1 - R_E)^n \, (R_E)^{NEXP-n} \qquad (4\text{-}10)$$

R_C = vibroacoustic reliability of a housekeeping component

R_E = vibroacoustic reliability of an experiment

The probability of obtaining data from all the experiments, P_0, is the probability of obtaining no failures during flight. The probability of obtaining data from all but n experiments, P_n, is the joint probability that none of the housekeeping components fail and that exactly n experiments fail and is determined using the binomial factor.

The probability of losing all the flight data, P_{NEXP}, is the sum of the joint probability that any of the housekeeping components fail and any number of experiments fail, and the joint probability that no housekeeping components fail but all the experiments fail. Considering each housekeeping component to be singly redundant with each section having a vibration reliability RVC and the structure having a reliability RVS, the vibroacoustic reliability of the series components in Equations (4-7) to (4-9) can be written as

$$\prod_{1}^{NCCE} (R_C)_i = (RVS)\,\{(RVC)(2 - RVC)\}^{NCCE-1} \qquad (4\text{-}11)$$

where the second term reflects the component redundancy. Similarly, the vibration reliability of the experiments, R_E, can be written as

$$R_E = \prod_{1}^{NCPE} (RVCE)_i \qquad (4\text{-}12)$$

where RVCE is the vibration reliability of a series component within an experiment.

Using the above expressions, the probability of losing a portion of the experiments during a flight can be determined for evaluating the cost of flight failures.

SECTION 5

DECISION MODEL

Statistical decision theory is used to formulate a model to determine the optimum test plan and the related test levels to be used. The decision tree or action space shown in Figure 5-1 defines the various alternatives considered in this study. In each test option the test level is treated as a variable, i.e., the component test level and the assembly test level are varied for all applicable options. This is indicated in Figure 5-1 by the fan shaped displays showing the component and assembly test levels as continuous variables. Having selected the test option, the "State-of-nature" or the probability of failures is estimated from the stress-strength statistical analysis of the component strength distribution and the environment distribution. The expected cost (C) can then be determined for each test option and associated test levels. It is assumed that cost provides a valid basis for selection of an optimum test plan since a realistic goal is to minimize project cost on a long range basis. To evaluate the expected cost for each option, deterministic or direct costs associated with a test option as well as the probabilistic costs must be determined. However, only cost changes associated with each test option are required since the common costs do not influence the selection of the optimum test plan.

The expected cost of a test option is determined by summing the direct costs and the expected costs associated with the test plan. This can be expressed mathematically as:

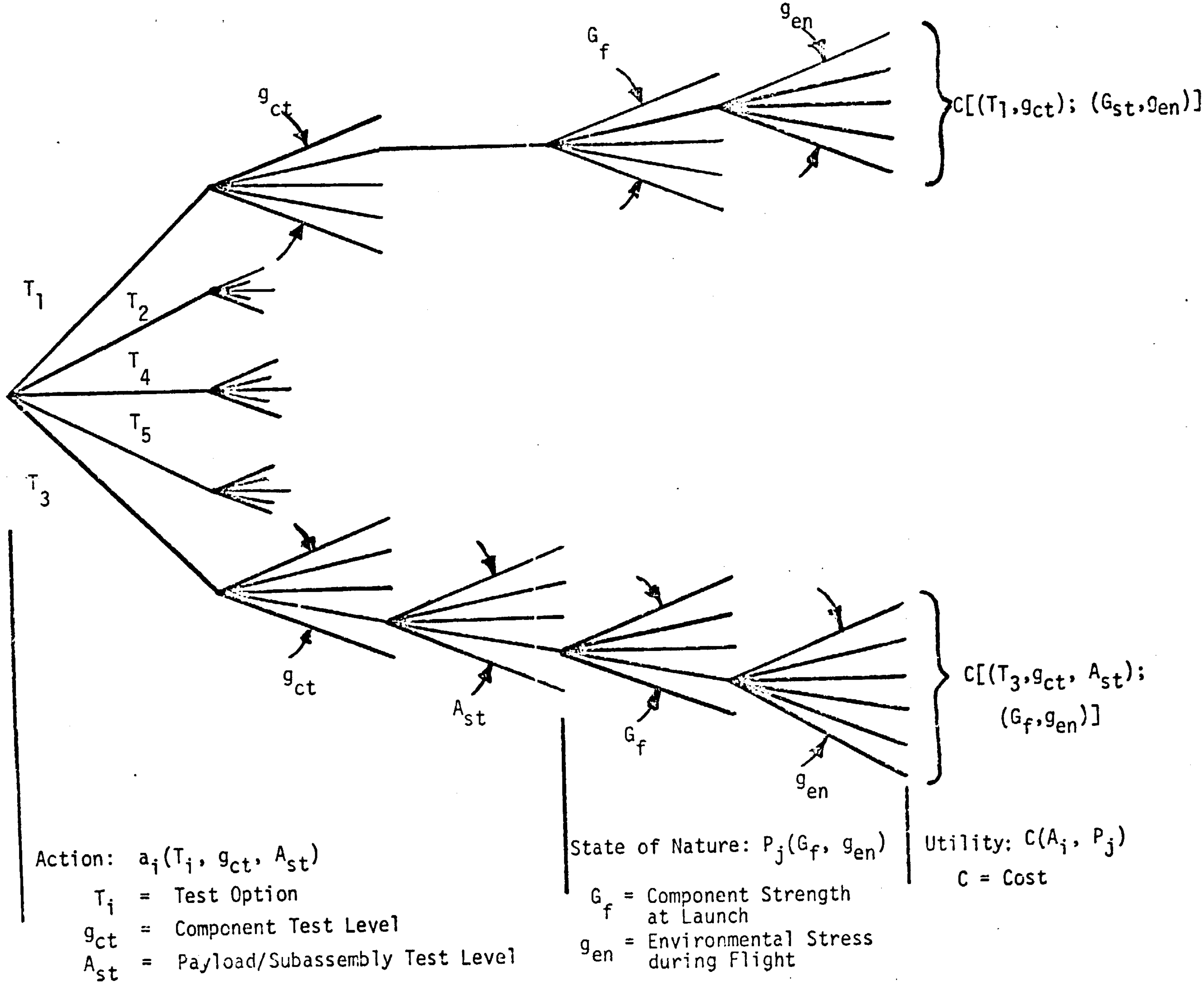


Figure 5-1 Decision Tree for Alternate Test Plans

as:

$$E\left\{C_{TX}\right\} = \sum_{i} P_i \, C_{Ei} + \sum_{j} C_{Dj} \qquad (5\text{-}1)$$

where

$E\left\{C_{TX}\right\}$ = Expected cost of test plan TX

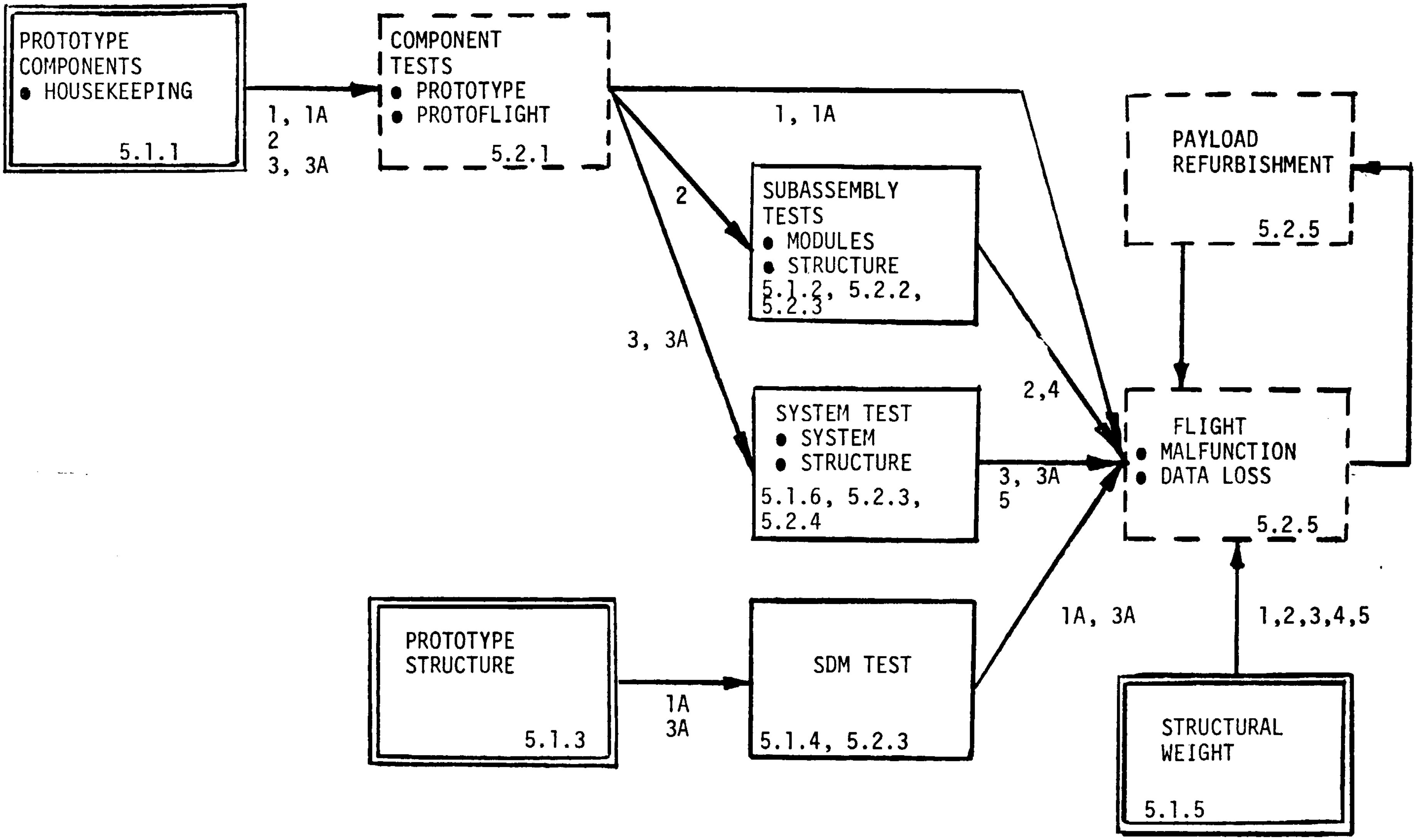
P_i = Probability of event i occurring

C_{Ei} = Cost incurred as a result of event i

C_{Dj} = Direct cost of decision j for the selected test plan

The cost elements must include all items peculiar to a selected test option.

Because of the similarity in the cost elements involved in the various test plans this section is organized by cost element. In Figure 5-2, the various costs involved in the test plans are indicated. The test plan number contributing to each element is shown adjacent to the arrows. The type of cost is indicated by the double, dashed and solid boxes designating direct, probabilistic, and combined direct and probabilistic cost, respectively. The applicable paragraph describing the cost element is indicated inside the box. For example, Test Plan 1 involves costs due to prototype components (direct), component tests (probabilistic), structural weight (direct), and flight and refurbishment (probabilistic). The direct costs are presented in Section 5.1 and the other probabilistic costs are presented in Section 5.2.



NOTE: Applicable test plans shown adjacent to arrows.
Applicable paragraphs shown in boxes.
═══ Direct Cost
– – – Probabilistic Cost
——— Direct and Probabilistic Cost

Figure 5-2 Decision Model Cost Flow

5.1 DIRECT COSTS

The direct costs are those costs which will be incurred by selecting a particular test plan regardless of the results obtained. Only those direct costs which are not common to all test plans need to be considered in order to determine the optimum plan. The cost elements that are considered in the evaluation of the various test plans are summarized in Table 5-1. They are shown in the solid and double boxes in Figure 5-2. The cost elements and the actual estimates are described in the following sections in the order shown in Table 5-1.

5.1.1 PROTOTYPE COMPONENTS

This is the cost of procuring an extra set of components to be used solely for the purpose of testing. These components are considered to be those used in the housekeeping subassemblies since all experiment components are protoflight tested using the actual flight hardware. The cost is determined for an average component so that the component costs can be increased for more complex payloads.

The average component cost is estimated to be $200,000. The cost was estimated considering a recurring cost of the housekeeping subassemblies of $7,000,000 of which half the cost is due to components. Considering a set of 16 components, this results in an average cost of $200,000. This cost was compared to that of typical housekeeping components and appears reasonable. Typical component costs vary from $87,000 to $500,000. The median and mean costs of a group of 15 components were approximately $200,000. Since these prototype components will be used for other tests as well as vibration (e.g., thermal vacuum, EMI, functional testing), only a portion of the total cost should be assigned to vibration testing. On this basis only one fourth of the component cost was assigned to vibration testing. This results in a direct cost of $800,000 for prototype components in Test Plans 1, 1A, 2, 3, 3A.

Table 5-1

SUMMARY OF DIRECT COST ELEMENTS FOR VARIOUS TEST PLANS

Cost Element	Test Plan 1	1A	2	3	3A	4	5
1. Prototype Components	X	X	X	X	X		
2. Subassembly and Experiment Tests			X			X	
3. SDM		X			X		
4. SDM Test		X			X		
5. Structural Weight	X		X	X		X	X
6. Protoflight Payload Test				X	X		X

5.1.2 SUBASSEMBLY AND EXPERIMENT TESTING

This is the cost of performing an acoustic test on a protoflight subassembly. The test, using a moderate amount of instrumentation, includes functional tests before and after excitation and monitoring during the test. The cost of a special fixture to support the subassembly is included. The costs of preparing a test plan and a report following the test are also included.

The cost is estimated to be $21,000. It is estimated on the basis of the following manhours and materials:

Engineering	344 hours @ $29.44
Drafting	60 hours @ $21.97
Technicians	350 hours @ $19.19
Manufacturing	120 hours @ $14.20
Material (fixture and test)	$1105.00

This cost is used for the three spacecraft housekeeping subassemblies (power, control, data handling). In this study each experiment is considered to be a subassembly. Thus, in Test Plans 2 and 4 the direct costs for subassembly and experiment testing are $84,000 for the single experiment payload configurations and $210,000 for the seven experiment payload configurations, respectively.

For Test Plans 2 and 4 a static test is performed on the structure. The cost of this test is $32,000 as described in Section 5.1.3.

5.1.3 STRUCTURAL DEVELOPMENT MODEL

This is the cost incurred in the construction of a dedicated payload structure to be used solely for test purposes. In reality, the SDM is used for other purposes following the completion of the test program. However, the complete fabrication costs of the structure and mass simulated components are included in this estimate.

The estimated SDM cost is $840,000. The cost was estimated from the actual costs of spacecraft SDM structures including a complexity factor to account for the simplified construction that will probably be used for Shuttle payloads. Although spacecraft SDM models can cost in excess of $1,000,000, the reduced cost of $840,000 should allow for the design complexity required for alignment, thermal control and other refinements of a payload structure, but still consider cost reductions that can be obtained where weight is not a major design factor. This direct cost of $840,000 for an SDM is used in Test Plans 1A and 3A.

5.1.4 STRUCTURAL DEVELOPMENT MODEL TESTING

This is the cost of performing static and dynamic tests on the SDM. The dynamic tests consist of a modal test and a random vibration or acoustic test. Typical accelerometer and strain gage instrumentation is considered to be recorded and reduced. The cost includes the preparation of the necessary procedures and the test report.

The estimated cost of $100,000 for static and dynamic tests of the SDM is based on current spacecraft testing costs. The following hours are included:

<u>Dynamic Testing</u>

Engineering	720 hours @	$21.97	
Technicians	2400 hours @	$19.19	
Material		$5,000	
			$67,000

<u>Static Testing</u>

Engineering	480 hours @	$21.97	
Technicians	1120 hours @	$19.19	
			$32,000

This direct cost of $100,000 for SDM testing is used in Test Plans 1A and 3A.

5.1.5 STRUCTURAL WEIGHT

This is the increased cost incurred by designing the structure to a higher safety factor so that a static test of an SDM is not required. As indicated previously, an ultimate design safety factor of 1.25 is considered applicable if an SDM test is performed. If no static test is performed, an ultimate safety factor of 2.0 is considered applicable. If the flight structure is proof tested, then an ultimate design safety factor of 1.5 is used. The structural weight of the SDM tested payload is used as a reference and the cost of increasing the structural weight through the use of a higher design safety factor has been estimated.

A study was performed to estimate the weight growth as a function of the safety factor. Data from Reference 3 and previous shuttle payload studies at GE indicate weight increases of 13 and 35 percent when the safety factor is varied from 1.25 to 1.50 and from 1.25 to 2.00, respectively. For this large optical payload, the structural weight of the payload was estimated to be 20 percent of the total payload weight, 1500 pounds. On this basis structural weight increases of 195 and 525 pounds were estimated for safety factors of 1.50 and 2.00, respectively.

Two current models for estimating STS user costs were reviewed to estimate the cost of increasing payload weight. The first model was that of E. Dupnick which develops a Services Rendered Unit (SRU) based on the weight, length, orbital inclination and altitude of the payload, Reference 13. With this model and the study payload weight, there was no cost of increasing the payload weight. Thus, this model was discarded in favor of the second model of H. Bloom, Reference 14. With this model there is an estimated cost increase of $166 per pound, considering a STS cost of $13,500,000 per flight. On a gross basis, the cost per pound for complete utilization of the STS launch capability is $210. It should be recognized, however, that the payload volume may be the controlling commodity. The $166 per pound rate was selected as being more representative, resulting in estimated costs per flight of increasing payload weight for safety factors of 1.50 and 2.00 of $32,370 and $87,150, respectively. 15 flights were considered for this study, so that the direct costs of $486,000 and $1,307,000 for structural weight were used in Test Plans 2, 3, 4, 5 and Test Plan 1, respectively.

5.1.6 PROTOFLIGHT PAYLOAD TESTING

This is the cost of testing a protoflight payload. For Test Plans 3 and 5 both dynamic and static tests are performed. For Test Plan 3A only dynamic tests are performed since the structural integrity is verified by the SDM. These costs are higher than the SDM cost because a crew is required for functional monitoring during the dynamic test. It is assumed that the static test of the protoflight structure can be performed prior to payload assembly and will not involve the system test crew.

The protoflight payload test cost is estimated to be $199,000 and $167,000 for Test Plans 3, 5 and Test Plan 3A, respectively. The cost of the static test is $32,000, as described above. The cost of the dynamic test, as described above, and the functional monitoring costs require the following hours:

Engineering	1680 hours @ $21.97
Technicians	6000 hours @ $19.19
Materials	$15,000

This provides an estimated cost of $167,000.

5.1.7 DIRECT COST SUMMARY

In Sections 5.1.1 through 5.1.6 values for the six direct cost elements given in Table 5-1 have been estimated. For convenience, these values are summarized in Table 5-2. The total direct costs for each test plan are obtained by summing the applicable direct cost elements for that particular test plan. Note that two columns of values are given for Test Plans 2 and 4. The first of these columns contains the values for the single experiment payload configurations and the second contains the values for the seven experiment payload configurations.

Table 5-2

Direct Cost Summary

Cost Element	Test Plan								
	1	1A	2		3	3A	4		5
			NEXP=1	NEXP=7			NEXP=1	NEXP=7	
Prototype Components	800	800	800	800	800	800	-	-	-
Subassembly Tests	-	-	84	210	-	-	84	210	-
SDM	-	840	-	-	-	840	-	-	-
SDM Test	-	100	-	-	-	100	-	-	-
Protoflight Structural Test	-	-	32	32	-	-	32	32	-
Protoflight Payload Test	-	-	-	-	199	167	-	-	199
Structural Weight	1307	-	486	486	486	-	486	486	486
Direct Costs	2107	1740	1402	1528	1485	1907	602	728	685

NOTE: Costs are given in thousands of dollars.

5.2 PROBABILISTIC COSTS

The expected costs are those costs which will result from failures during ground testing and flight. According to Equation (5-1), the actual value of the expected cost is the product of the probability of occurrence and the cost elements described in this section. The cost elements that are considered in the evaluation of the various test plans are summarized in Table 5-3. In Figure 5-2 they are shown in the solid and dashed boxes. The cost elements and the actual estimates are described in the following sections in the order given in Table 5-3.

Table 5-3

Summary of Expected Cost Elements For Various Test Plans

Cost Element	Test Plan						
	1	1A	2	3	3A	4	5
1. Component Test Failures	X	X	X	X	X		
2. Subassembly Test Failures			X			X	
3. Structure Test Failures		X	X	X	X	X	X
4. Payload Test Failures				X	X		X
5. Flight Failures	X	X	X	X	X	X	X

5.2.1 COMPONENT TEST FAILURES

The special Pascal distribution, Equation (4-4), is used to obtain the expected cost of component test failures, expressed mathematically in Equation (5-2).

$$E\{C_{ctf}\} = NC \left[\sum_{x=1}^{50} x \cdot (1 - \theta)^{x-1} \cdot \theta \cdot \$15{,}000 \right] - \$7{,}000 \quad (5\text{-}2)$$

where NC = number of components = number of redundant housekeeping components plus number of experiment components

θ = probability of a component passing the test

x = number of tests

\$15,000 = cost of component redesign/retest

\$7,000 = cost reduction for initial test of each component

The \$7,000 cost reduction is subtracted from the expected cost to reflect the reduced cost of the initial component test. All additional component tests include redesign/retest costs.

The cost of a component test is the cost of performing a vibration test on an electronic package. Using a limited amount of instrumentation, the test is performed in three axes and includes functional tests before and after vibration. The cost of a flat plate fixture to adapt the component to the shaker is included. Also included are the costs of preparing a test plan and a report following the test. The cost is estimated to be \$8,000, on the basis of the manhours and materials required as follows:

Engineering	182 hours @ \$29.44
Drafting	16 hours @ \$21.97
Technicians	92 hours @ \$19.19
Manufacturing	17 hours @ \$14.20
Material (fixture and test)	\$100.00

The cost of a component test failure includes the cost of the corrective action required to pass the test. An average cost estimate of a failure during component testing was made considering a five week span to redesign, repair and retest the component. In general, there will be a relatively small group of engineers, technicians and manufacturing personnel directly involved with the component failure. This involves approximately a three week span for rework and repair followed by a two week span for retesting the component. The cost is estimated to be $15,000 on the basis of the following manhours and materials:

Engineering	260 hours @ $29.44
Drafting	80 hours @ 21.97
Technicians	200 hours @ 19.19
Manufacturing	80 hours @ 14.20
Material (fixture and test)	$600.00

It will be noted that it is significantly higher than the component test cost since corrective action and retesting are included.

The expected cost of a component test is used in Test Plans 1, 1A, 2, 3, 3A, while the expected cost of a component test failure is used in all test plans.

5.2.2 SUBASSEMBLY TEST FAILURES

The special Pascal distribution, Equation (4-4), and the binomial distribution, Equation (4-5), are used to obtain the expected cost of subassembly test failures that do not involve any schedule delays. This is expressed mathematically in Equation (5-3) for each subassembly:

$$E\{C_{stf}\} = [1 - P_b(0)] \quad \$13{,}000 + \sum_{I=1}^{N} P(I) \quad I \quad \left(\sum_{x=1}^{50} x \quad (1-\theta)^{x-1} \quad \theta \quad \$15{,}000 \right) \tag{5-3}$$

where N = number of components in subassembly

θ = probability of a component passing the test

x = number of retests

$P_b(0)$, $P_b(I)$ = binomial probabilities of zero or I component failures during subassembly tests, treating both sides of redundant components

\$13,000 = cost of subassembly functional test

\$15,000 = cost of component test failure

The first term of Equation (5-3) is the expected cost of a subassembly functional test which is performed if any component failure occurs. The second term is the component redesign/retest cost. This model considers all component failures to be corrected at the component level without additional acoustic tests of the subassembly.

The cost of a subassembly test failure includes the cost of the corrective action required to pass the test. Since subassembly testing is done in parallel, there is only a small effect on the overall project schedule. The subassembly functional test cost is estimated to be \$13,000 on the basis of the manhours and materials required as follows:

Engineering	360 hours @ \$29.44
Technicians	120 hours @ \$19.19
Materials	\$300.00

Retest failures that occur during component testing do not have a major effect on the overall program schedule since the subassemblies are tested in parallel. Hence, the component retest cost can be applied. The cost of one component redesign/retest cycle is estimated to be \$15,000 as in Section 5.2.1.

The above costs of subassembly test failures are applied to all housekeeping subassemblies and all but one experiment. For one experiment a schedule delay is considered. In this case the binomial distribution, Equation (4-5), and the general Pascal distribution, Equation (4-6), are used to obtain the expected cost of subassembly test failures. Equation (5-4) expresses this mathematically:

$$E\{C_{stf}\} = \sum_{I=1}^{N} P_b(I) \quad \$120{,}000 \quad (1 + I) \; +$$

$$\sum_{I=2}^{N} \sum_{x=I}^{50} P_b(I) \quad \left(\frac{\theta}{1-\theta}\right)^I \quad \frac{(x-1)!}{(I-1)!\;(x-I)!} \quad (1-\theta)^x \quad \frac{\$120{,}000}{I} \quad (x-1) \tag{5-4}$$

where
- N = number of components in the experiment
- θ = probability of I components passing the test
- x = number of retests
- $P_b(I)$ = binomial probabilities of I component failures during the experiment test
- \$120,000 = subassembly test failure cost factor

The first term of Equation (5-5) is the expected cost of subassembly testing if any component failure occurs without component repair. This test is a major milestone in the development of the spacecraft and is treated as an in-line item. Failures occurring during this phase of a program cause schedule slips which can best be costed by considering the number of personnel in the program. It is estimated that a cost of \$120,000 per week will result if the program slips. The amount of slippage that occurs depends on the number of failures. A two week slip was considered for the first failure; this provides the required time for repair and retest. An additional week slip is considered for each failure until N failures occur.

The second term of Equation (5-5) is the retest/repair cost on the component level. Retesting results in an additional schedule slip of one week when I components fail and I + 1 retests are required. It is assumed that the failures will be corrected separately on each component on a component level prior to continuing subassembly testing.

These expected costs are used in Test Plans 2 and 4.

5.2.3 STRUCTURE TEST FAILURES

The expected cost of structure test failures depends on the type of structure considered. In Test Plans 1A and 3A a prototype structure (SDM) was tested and a design safety factor of 1.25 was used. The cost of an SDM test failure includes the cost of repairing and retesting the SDM after a failure occurs during testing. It is assumed that the failure is not catastrophic such as would occur during an acceleration test. The estimated cost of an SDM test failure is $150,000. This is equivalent to 30 people for a four week period. Considering the difficulty in repairing a structural failure, this appears to be a reasonable estimate. Since the SDM testing is not an in-line function, it is not appropriate to consider overall program schedule slippage. However, a significant number of personnel are required to determine the corrective action required, to repair the structure, and to retest. The cost of structural failures can vary considerably. Equation (5-1) was used to combine this cost of $150,000 for an SDM test failure with the probability of a prototype structure failure occurring (0.34 as given in Section 4.6) to obtain the constant expected cost of $51,000 for an SDM test failure. This value is used in Test Plans 1A and 3A.

In Test Plans 2, 3, 4, 5 a protoflight structure was tested with a design safety factor of 1.5. For Test Plans 2 and 4 the cost of a structure failure was estimated to be $150,000, as in the SDM test described above. For Test Plans 3 and 5, however, the structure test is an in-line function and the cost of a structure failure was estimated to be $240,000. Equation (5-1) was used to combine these costs with the probability of a protoflight structure failure occurring (0.04 as given in Section 4.6) to obtain the expected cost of $6,000 for Test Plans 2 and 4 and $9,600 for Test Plans 3 and 5, respectively.

5.2.4 PAYLOAD TEST FAILURES

The expected cost of payload test failures includes the cost of repairing and retesting the protoflight payload after failures occur during test. This cost is based on an overall program schedule slippage and is similar to that described in Section 5.2.2 for the one experiment that caused schedule delays when a failure occurred during subassembly testing. Equation (5-4) is applied twice to evaluate the expected cost of payload test failures since the housekeeping components and experiment components have different binomial probabilities and probabilities of a component passing the test. These expected costs are used in Test Plans 3, 3A, and 5.

5.2.5 FLIGHT FAILURES

The expected cost of flight failures includes the cost of incurring the loss of mission objectives during flight and the subsequent cost of refurbishing the payload after flight. The loss of data from each experiment is weighted equally so that a loss of a portion of the experiments during flight causes a corresponding portion of the single mission cost to be attributed to flight failures.

The cost of a complete loss of data is estimated to be equal to the cost of the flight. The flight cost attributable to this payload is estimated to be approximately 25 percent of the STS cost per flight. Using the SRU relation of Reference

13 for a payload weight of 7500 pounds, a payload length of 15 feet, an altitude of 200 nautical miles and a variable orbital inclination, the STS cost for the payload varied from approximately 15 percent to 35 percent. Considering the gross effect of length as 25 percent of the payload compartment and the gross effect of returnable weight as 23 percent of the STS capability, a 25 percent cost estimate was selected. The STS cost per flight was assumed to be \$13.5 M. For those configurations having an increased weight due to the structural design safety factor, one fifteenth of the cost of the weight was included in the flight cost. The cost of flight failures that result in the loss of data can be written as

$$E\{C_{\ell d}\} = \sum_{i=1}^{NEXP} P_i \; C_i \tag{5-5}$$

where P_i = probability of losing data from i experiments, Equations (4-8) and (4-9)

C_i = cost of losing data from i experiments during flight

= launch cost ÷ NEXP

Several guidelines were established to evaluate the expected costs of refurbishing a payload after flight failures occur. The payload will normally be shipped to the laboratory between flights for revision and modification. Flight failures are worked on a component level resulting in redesign as well as repair. Additional functional tests, which would not have been required normally, are required as a result of rework. The probability of component failure during the repair cycle corresponds to that associated with the component 23 g RMS vibration requirement. This value was selected as a relatively severe test presuming that flight data at the particular component location was not available. The repair/retest is not an in-line function because scheduled flights occur at six month intervals. Within these guidelines the expected cost of refurbishment can be expressed mathematically as

$$E\{C_{rf}\} = [1 - P_b(0)] \quad \$16{,}000 + \sum_{I=1}^{N} P_b(I) \quad I \quad \left(\sum_{x=1}^{50} x \quad (1-\theta)^{x-1} \quad \theta \quad \$15{,}000 \right) \tag{5-6}$$

where N = number of housekeeping components or number of experiment components

θ = probability of a component passing the test

x = number of retests

$P_b(0)$, $P_b(I)$ = binomial probabilities of zero or I component failures during flight, treating both sides of redundant components

\$16,000 = cost of an additional functional test

\$15,000 = cost of a component test failure

The first term of Equation (5-5) is the expected cost of the additional functional test required if any component failure occurs during flight. The second term is the retest/repair cost on the component level. Note that the special Pascal distribution, Equation (4-4), and the binomial distribution, Equation (4-5), are used to obtain the expected cost of refurbishment. Also note that Equation (5-5) is applied twice since the housekeeping components and experiment components have different binomial probabilities and probabilities of a component passing the test.

The cost of the additional functional test is estimated to be \$16,000 on the basis of the following manhours:

Engineering	320 hours @ \$29.44
Technicians	320 hours @ \$19.19

Retest failures that occur during component testing do not have a major effect on the overall program schedule since the flights occur at six month intervals. Therefore, the component retest cost can be applied. In Section 5.2.1 this cost is estimated to be $15,000.

The expected cost of flight failures is obtained by combining Equations (5-5) and (5-6) with the number of missions. This is expressed mathematically in Equation (5-7).

$$E\{C_{ff}\} = 15 \quad [E\{C_{\ell d}\} + E\{C_{rf}\}] \tag{5-7}$$

These expected costs of flight failures are applied in the same manner in all test plans.

5.2.6 PROBABILISTIC COST SUMMARY

In Sections 5.2.1 through 5.2.5 the five expected cost elements given in Table 5-3 have been described and the applicable costs have been estimated. For convenience, cost parameters for these expected cost elements are summarized in Table 5-4. It should be noted that these are cost parameters that appear in Equations (5-2) through (5-7) and no attempt should be made to obtain expected costs from these numbers.

5.3 MODELING SIMPLIFICATIONS AND ASSUMPTIONS

At this point it is felt that the simplifications and assumptions that have been made in developing the decision model should be summarized. At each step in the development, the considerations have been described but the modeling complexity makes it difficult to recall all the details of the development. In addition, some simplifications inherent in the modeling need to be identified. These items are summarized below.

TABLE 5-4

Summary of Cost Parameters for Expected Cost Elements for Various Test Plans

	Test Plan						
Cost Parameter	1	1A	2	3	3A	4	5
Cost of Component Test	8.	8.	8.	8.	8.	-	-
Cost of Component Redesign/Retest	15.	15.	15.	15.	15.	15.	15.
Cost of Subassembly Functional Test	-	-	13.	-	-	13.	-
Subassembly Test Failure Cost Factor	-	-	120.	-	-	120.	-
Cost of SDM Test Failure	-	150.	-	-	150.	-	-
Cost of Protoflight Structure Failure, Subassembly Testing	-	-	150.	-	-	150.	-
Cost of Protoflight Structure Failure, Payload Testing	-	-	-	240.	-	-	240.
Payload Test Failure Cost Factor	-	-	-	120.	120.	-	120.
Cost of One Launch	3462.	3375.	3407.	3407.	3375.	3407.	3407.
Cost of Additional Functional Test After Refurbishment	16.	16.	16.	16.	16.	16.	16.

NOTE: Costs are given in thousands of dollars.

1. Payloads - The study has been restricted in scope to facility type payloads of varying complexity. Payload variables include the number of experiments and the number of components comprising an experiment. However, all payloads are flown on 15 missions at the rate of 2 per year. The generalization of these study results to specialized payloads used for one or two missions is incorrect.

2. Test Plans - Five basic test plans with two variations have been studied. The use of the results to anticipate trends for other candidate programs may be misleading if all the factors involved are not properly considered. A no-test option has not been addressed in this study.

3. Shuttle Environment - The shuttle 97.7 percentile acoustic environment is considered to be 145 dB with the spectrum shape defined in the STS Payload Accommodations volume. The acoustic environment is considered to have a log normal distribution with a standard deviation of 2 dB. It is a major factor in determining the flight failure probabilities. Changes in the environment will influence the costs of the various test plans and the optimum test levels. The vibration environment is considered to result primarily from lift-off acoustic excitation neglecting mechanically transmitted payload excitation through the support structure. The component environment is considered to be similar to that of internally mounted components on current spacecraft. The influence of the shuttle environment on the optimization of the test plans was not investigated in this study.

4. Component Defects - The study is directed toward systematic defects caused by design deficiencies. Random defects caused by poor workmanship, defective parts and other sources are not included in this study.

5. Component Vibration Strength - The untested component vibration strength is treated as a log normal distributed random variable using relationships derived empirically from data on previous spacecraft programs. The strength is considered to be modified significantly by the test program and design level requirements. The effects of vibration tests prior to flight are included using a g^3t relationship to account for fatigue effects and the possibility of incipient failures. A limited ability to design components for vibration is considered but major changes in the vibration strength result from testing.

6. Assembly Level Test Environment - The component environment during subassembly and payload testing is considered to accurately simulate the flight environment. Both test environments are considered to be equally effective in providing a realistic simulation of flight conditions. The only parameter resulting in differences between assembly test conditions and flight is the acoustic level. It is assumed that distinct subassemblies exist.

7. Test Effectiveness - Tests at all levels of assembly are considered to be equally effective in locating design defects. The model considers the defects to be a function of the vibration level. Consequently, any test which exposes the component to a sufficiently high level will cause a failure. This may be a significant simplification since past experience has shown system level testing to be a more effective test screen.

8. Primary Structure - The primary structure is treated in the same manner as the study by Thomas, Reference 3. It recognizes the ability to significantly affect the strength through the use of higher safety factors. A "no test" option has been included in Test Plan 1, an SDM "standard test" option has been included in Test Plans 1A and 3A, and a protoflight "proof test" option has been included in all others. Typical design safety factors are used with each plan but they are not varied to determine the optimum value. The cost of a prototype structure and the cost of increased weight due to higher safety factors are included in the model. The study addresses the reliability of primary structure only and does not consider the possibility of secondary structure failures.

9. Component Design Cost - The cost of designing components has been considered to be independent of the vibration design or test level. It is recognized that the current technology of spacecraft component design is limited and that new design techniques may be required for the higher vibration levels considered in this study. However, variations of the requirements within the range currently used for component design may have little effect on cost. This cost should be investigated more thoroughly.

10. Component Cost - The cost of test dedicated components are included for those test plans using prototype components. However, only one fourth the cost is used since the components will also serve other functions. No component costs are considered for protoflight test programs.

11. Component Test Costs - The cost of component testing includes component retest/redesign costs based on the probability of a component failing the test. As a result the cost of developing components for high vibration levels is treated in the model for those test plans including component tests. The component testing is considered to be performed as a parallel project activity and does not pace the program. No schedule slippage cost is included.

12. Subassembly Test Costs - Subassembly testing is considered to be a parallel project activity for all payload subassemblies and for all but one experiment The cost of project schedule slippage is included for one experiment subassembly in the same manner as for payload testing. Failures during subassembly testing are considered to be worked on a component basis using costs similar to those used for component testing. The cost of component redesign/retest as a result of subassembly failures is underestimated if it is necessary to return the component to the vendor for rework and negotiate a contract with him. This cost needs to be investigated further.

13. Payload Test Cost - In addition to the direct cost of performing the payload test, failures occurring during payload testing are considered to result in project schedule slippage with the related cost of the project team. The cost is related to the number of failures which occur with additional cost increases due to retesting. The same cost model used for payload testing is also used for one subassembly.

14. Flight Data Loss - The payload is modeled as a series of redundant housekeeping subassemblies composed of singly redundant components and a set of parallel experiments each composed of a series of nonredundant components. With this model, partial loss of payload data is considered if an individual experiment fails while only half of a redundant housekeeping component fails. The cost of experiment failures during flight is equally divided among the experiments using a payload flight cost of approximately $3,400,000. The number of experiments and the number of components comprising an experiment are variables. However, all failures are considered to result from component failures. In this study, flight vibroacoustic reliability is defined as the probability of no experiment data loss during a flight.

15. Flight Refurbishment Cost - If any component malfunctions during flight, the payload is considered to be refurbished prior to the next flight. It is assumed that the payload would normally be returned to the laboratory for recalibration and possible upgrading between flights and that there is a relatively long period (6 months) between flights. Payload refurbishment due to component failures is considered to consist of an additional functional test and the redesign/rework of components on the component level of assembly. The component cost is similar to that used for assembly and component testing and is underestimated if a vendor rework with added contractual negotiations is required. The model considers adequate time to be available between flights so that project schedule slippage is not involved.

16. Flight Failure Probability - The flight failure probability is based on an average exposure duration over the total number of flights. This has been used to make the analysis more tractable.

SECTION 6

TEST PLAN EVALUATION

The results obtained from applying the decision models to the various test plans are presented and discussed in this section. The section is divided into three parts. Section 6.1 discusses the results obtained on the basis of cost optimization. Section 6.2 discusses the combined influence of cost and reliability. Section 6.3 discusses the applicability of the results and some of its ramifications.

6.1 COST OPTIMIZATION

The decision model for each test plan (TP) was exercised for four payload configurations. The payloads were all of the facility type having 15 planned flights. The payload complexity was varied by considering either one or seven experiments, with each experiment comprised of either one or six serial components. The housekeeping section of the payload was not changed and consisted of three subassemblies having a total of 16 redundant components and the structure.

The expected cost as a function of both the component vibration level and the applicable assembly test level are shown in Figures 6-1 to 6-4 for each of the payload configurations. The first six parts of each figure show the expected cost for each of the test plans and the last part(g) compares the various test plans for the assembly test level that minimizes the expected cost. The vibration level, used as the abscissa for each curve, has a dual meaning. For those TP's having component testing, the vibration level is the component qualification test level while for TP4 and TP5, which do not include component testing, it represents the component design requirement. As described in Section 3, the component strength distribution is considered to be a function of the component design/test level so that the vibration strength of the untested components continually increases as the vibration level is increased. The vibration level is shown in terms of its RMS g level and also as the standardized vibration variable, U_v, of the flight environment.

Optimum test levels are clearly defined for Test Plans 1, 1A, 2, 3 and 3A. Examination of the curves for these test plans indicates that the expected cost is minimized for component test values between approximately 13 g RMS and 63 g RMS with assembly test levels between 147 and 153 dB. For Test Plans 4 and 5, which do not include component tests, no optimum is defined since the component design strength can be increased indefinitely without incurring an increase in component design and development cost. This is obviously unrealistic but has not yet been quantified. In lieu of this cost, the curves for TP4 and 5 should be considered applicable only over the range of current component design strengths which can be achieved without significant departures from existing design practice. For current spacecraft components this is in the range from 10 to 20 g RMS. It will be noted, however, that component redesign/retest costs are included in the TP4 and TP5 models after failures occur during assembly level testing. It should also be noted that there is a well-defined optimum assembly test level for TP4 and TP5 in the applicable range of component vibration strengths. In Figure g, the optimum curves for TP4 and 5 were selected using the optimum assembly test level corresponding to a component vibration level of 13.5 g RMS.

Comparison of the expected costs for the optimum assembly test level (Figure g) indicates that TP2, 4, and 5 are the most attractive. Minimum cost is achieved with TP4 which involves subassembly testing only, for all of the payload configurations analyzed. However, the optimum test level for TP4 varies from 151 dB to 155 dB. System level testing only, TP5, ranks next to TP4 followed closely by TP2, which includes both component and subassembly testing. Component testing only (TP1 and 1A) and component and system testing (TP3 and 3A) are considerably less cost effective with TP1 and 1A being the least effective by a large margin.

A major reduction in direct cost is realized by eliminating dedicated test hardware which is included in all the test plans except TP4 and TP5. This is a direct cost of $800,000. In addition, component test costs neglecting retesting account for an additional $144,000 to $464,000 for the payload configurations having the smallest and largest number of components, respectively. Because the subassembly testing is considered to be as accurate a simulation as the system level test and can be done in parallel for all but one subassembly, subassembly testing enables only those marginal component designs at locations having a high response to be identified and corrected at minimum cost. High test levels are used to obtain a relatively high flight reliability. In this decision model, the cost of a component failure during subassembly testing is very nearly the same as that during component level testing. This is reasonable if the component is developed by the subassembly contractor but would be unrealistic and probably should be increased if the component were purchased.

Although the test plan ranking is not affected by the payload configurations analyzed in this study, the optimum test levels vary. The optimum test levels for each of the four payload configurations are shown in Table 6-1. The payload flight vibroacoustic reliability is also indicated. In this study, the flight vibroacoustic reliability is defined as the probability of no data loss from the payload as a result of a vibration failure of a component. The table indicates that the highest test levels result for the payload having a single experiment consisting of six components. This is consistently true for all the test plans. This appears to be due to the increased probability of a complete data loss for the single experiment configurations. The test levels are consistently lowest for the payload having

Table 6-1. Summary of Optimums by Test Plan

Test Plan	Payload Configuration (NEXP, NCPE)	Expected Cost ($ X 10^6)	Assembly Test SPL (dB)	Component Vib. Level (g RMS)	Vibroacoustic Reliability
1	1,2	4.275	-	48	0.9833
	1,6	5.793	-	63	0.9672
	7,2	4.785	-	48	0.8934
	7,6	7.577	-	48	0.7142
2	1,2	2.243	153	13	0.9982
	1,6	2.628	153	23	0.9961
	7,2	2.630	151	13	0.9793
	7,6	3.575	153	13	0.9626
3	1,2	2.700	149	23	0.9967
	1,6	3.096	151	29	0.9949
	7,2	3.107	147	23	0.9657
	7,6	4.367	149	23	0.9335
4	1,2	0.995	153	13*	0.9981
	1,6	1.383	155	13*	0.9966
	7,2	1.204	151	13*	0.9786
	7,6	1.756	153	13*	0.9613
5	1,2	1.728	149	13*	0.9949
	1,6	2.243	151	13*	0.9907
	7,2	2.000	147	13*	0.9467
	7,6	3.059	149	13*	0.9007

*Representative component design strength with current technology.

seven experiments with two components each. For this configuration, higher reliability is achieved with lower assembly test levels in comparison to the other configuration having seven experiments. It should be noted that both seven experiment configurations optimize cost at a lower reliability than the single experiment configurations.

Comparison of expected costs for Test Plans 1, 1A, 3 and 3A indicates the protoflight "proof test" loading of the structure appears to be the most cost effective. Comparing the cost of TP1 and 1A indicates the cost change between an untested overdesigned structure (TP1) and a prototype tested structure (TP1A). For these multiple mission facility payloads, the increased weight resulting from a conservative design results in a greater cost increase than the deletion of the prototype structure and test. Comparison of TP3 and TP3A indicates that a "proof loaded" protoflight structure (TP3) results in a larger cost saving than the less conservatively designed prototype tested structure (TP3A). However, it must be kept in mind that the study only addresses the multi-mission facility type payload.

The major cost elements involved in establishing the optimum test levels can be seen by examining the optimum for the payload configuration having seven experiments with six components each. Figures 6-5 (a) through (e) show the major cost elements for the optimum assembly test level for each of the five basic test plans. For TP1, shown in Figure 6-5 (a), the optimum results from the increasing cost due to component test failures combined with the decreasing cost due to flight failures. For TP2, shown in Figure 6-5(b), the decreasing costs of both subassembly test failures and subsequent flight failures interact with the increasing cost of component test failures to provide a relative broad range for optimum component test level selection.

Similar cost interactions are indicated for TP3 in Figure 6-5 (c) with a more pronounced optimum due to the higher system test failure cost. For Test Plans 4 and 5, the decreasing cost of assembly test failures and flight failures with increasing component strength fails to provide an optimum component design level since there is no increased cost associated with the higher component design strength.

For many of the test plans, a considerable amount of latitude exists in selecting the test level without incurring a large increase in expected cost. In reality, the short term success of major projects is a real consideration that must be addressed by the project manager. To select an optimum test level, the variation in the probability of a project success with test level selection must also be considered. This is discussed in the next paragraph which examines the influence of test levels on both cost and reliability.

6.2 RELIABILITY AND COST OPTIMIZATION

For those test plans which exhibit a range of test levels with small changes in the expected cost, the flight reliability of the payload as well as the expected cost should be considered in selecting test levels. To examine this effect the minimum cost and constant cost contours for costs 5 and 10 percent above the minimum were superimposed on graphs showing the variations in flight failure probability with test levels. (The flight failure probability is the probability of losing data from any experiment during a flight.) The resulting curves for Test Plans 1, 2 and 3 are shown in Figures 6-6 to 6-9 for each of the four payload configurations analyzed. Also included in the figures are the flight reliabilities for the other basic plans.

The results indicate that for those test plans using component and assembly level testing, significant reductions in the flight failure probability can be obtained by increasing the assembly test level. The desired short term goal of minimizing the flight failure probability is indicated on the graphs by the lowest point within the constant cost contour. These low points occur for relatively small increases in the component test level (e.g., on the order of 0.1σ for a five percent cost increase for TP3) but a relatively large increase in the assembly level (e.g., 4dB corresponding to a 2σ change for a five percent cost increase for TP3). This appears to indicate that a large gain in payload reliabiility can be achieved at minimum cost by increasing the severity of the assembly test environment which is considered to accurately simulate the flight conditions. This will selectively excite the payload components at relatively high flight levels and result in selective redesigns of components which will experience a high vibration level in flight. Although the assembly test level seems more severe than would have been anticipated, the high test level reduces the incipient failure probability.

A summary of the minimum cost test plan levels, the minimum project cost and the flight reliability are shown in Table 6-2. In general, the test plans with minimum cost also have maximum reliability. The exceptions are TP2 and TP5. TP2 provides a higher flight reliability than TP5 but also results in an increased project cost. If protoflight component testing were used in TP2, a direct cost savings of $800,000 would be obtained. TP2 would then rank second on the basis of both cost and flight reliability. Subassembly testing appears to provide the best approach to the development of low cost high reliability facility type payloads.

6.3 APPLICATION OF RESULTS

This study of a facility type Shuttle Spacelab payload indicates several trends. It does not appear that testing should be eliminated but rather that relatively high test levels should be used, particularly for assembly level testing. The deletion of dedicated test hardware appears to be a significant direct savings that cannot be overlooked for future low cost programs. Perhaps the most challenging trend is that of deleting component testing and using subassembly or system level testing to obtain a high flight vibration reliability.

The deletion of component tests is not consistent with current contractual practices. In most programs, components are procured to specifications which require that the component pass a qualification test. The component supplier has the responsibility of designing or redesigning the component such that it does pass the test. If component testing is not required, the cost of subsequent redesign/retest of components which fail during assembly level testing probably is not the component suppliers' responsibility and may become inflated as the result of negotiations. One approach to circumvent these costs would be to require a

Table 6-2. Summary of Optimums by Payloads

Payload Configuration (NEXP, NCPE)	Test Plan	Expected Cost ($ x 10^6)	Assembly Test SPL (dB)	Component Vib. Level g (RMS)	Vibroacoustic Reliability	Cost Rank	Reliability Rank
1, 2	1	4.275	-	48	0.9833	7	6
	1A	3.938	-	48	0.9828	6	7
	2	2.243	153	13	0.9982	3	1
	3	2.700	149	23	0.9967	4	3
	3A	3.196	149	29	0.9961	5	4
	4	0.995	153	13*	0.9981	1	2
	5	1.728	149	13*	0.9949	2	5
1, 6	1	5.793	-	63	0.9672	7	6
	1A	5.435	-	63	0.9667	6	7
	2	2.628	153	23	0.9961	3	2
	3	3.096	151	29	0.9949	4	3
	3A	3.581	151	29	0.9936	5	4
	4	1.383	155	13*	0.9966	1	1
	5	2.243	151	13*	0.9907	2	5
7, 2	1	4.785	-	48	0.8934	7	6
	1A	4.448	-	48	0.8929	6	7
	2	2.630	151	13	0.9793	3	1
	3	3.107	147	23	0.9657	4	3
	3A	3.592	147	23	0.9645	5	4
	4	1.204	151	13*	0.9786	1	2
	5	2.000	147	13*	0.9467	2	5
7, 6	1	7.577	-	48	0.7142	7	6
	1A	7.198	-	48	0.7139	6	7
	2	3.575	153	13	0.9626	3	1
	3	4.367	149	23	0.9335	4	3
	3A	4.849	149	23	0.9323	5	4
	4	1.756	153	13*	0.9613	1	2
	5	3.059	149	13*	0.9007	2	5

*Representative component design strength with current technology.

warranty from the supplier that would provide redesign if a failure does occur. Another alternative would be to control the component design such that adequate strength would be assured. It will be noted that the decision model used for evaluating the test plans provides a fixed component redesign/retest cost for all levels of testing which is optimistic with present contracting practices. To gain the cost savings indicated for TP4 and TP5, current contractual relations with component suppliers would have to be modified.

It is recognized that, in the course of payload project planning, an effort must be made to eliminate workmanship problems incurred during the fabrication and integration process. Often, some form of vibroacoustic test is used to screen such defects. As stated earlier, such failures were not considered in the course of this study primarily because representative failure data was not available. How consideration of such failures would affect the results of this study, however, would require speculation. What can be stated at this time is that, with the exceptions of Test Plans 1 and 1A, all test plans considered in the study conduct a vibroacoustic test of all hardware that is to fly at a level sufficiently high to detect workmanship defects. Since TP1 and TP1A are consistently the more expensive and less reliable, selection of any of the test plans indicated to be cost effective by this study, therefore, has the inherent capability to uncover workmanship failures. It is unlikely that workmanship defects would influence the selection of TP2 over TP3 or the selection of TP4 over TP5 since similar costs would be incurred during component testing. The selection of TP2 over TP4 or the selection of TP3 over TP5 may be influenced by workmanship defects if no test screen is provided until assembly level testing is performed. Once again, the influence of such failures, and their corresponding costs, on the resulting optimum test plan and its associated test levels was not evaluated in this study.

The objective of this study is significantly different than that of Campbell, Reference 15. In Campbell's study, the objective is to relax reliability requirements for experiments by allowing multiple flights. In this study, the objective is to determine methods of achieving minimum cost by optimizing test plans. It should also be noted that this study has addressed a multi-mission facility type payload rather than the single mission experiment examined in Campbell's investigation. However, the basic difference is that this study is directed toward the quantitative evaluation of alternate test plans to minimize cost, whereas the Campbell study addresses the overall payload reliability in a more qualitative manner.

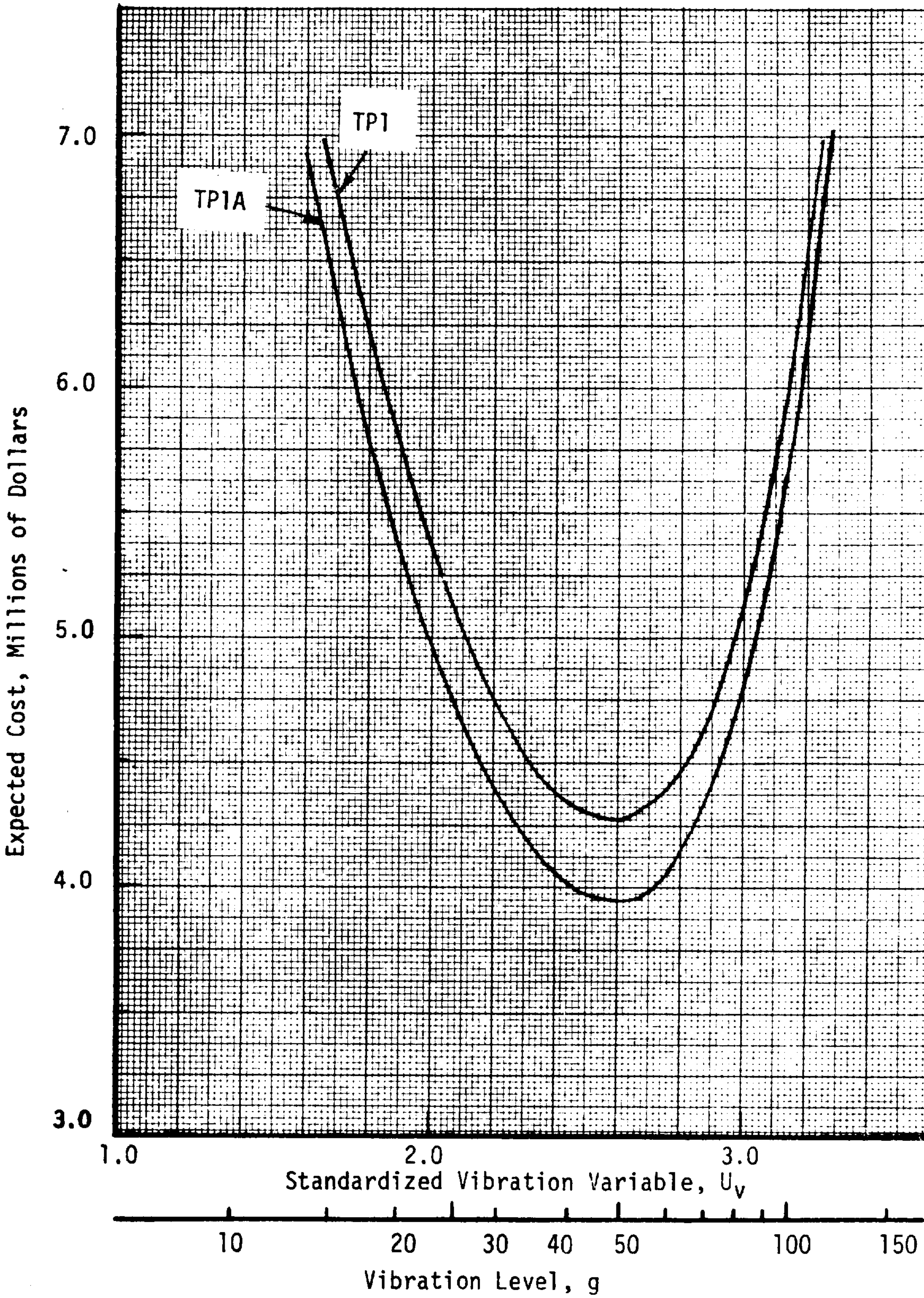


Figure 6-1(a) Test Plans 1 and 1A Costs, NEXP=1, NCPE=2

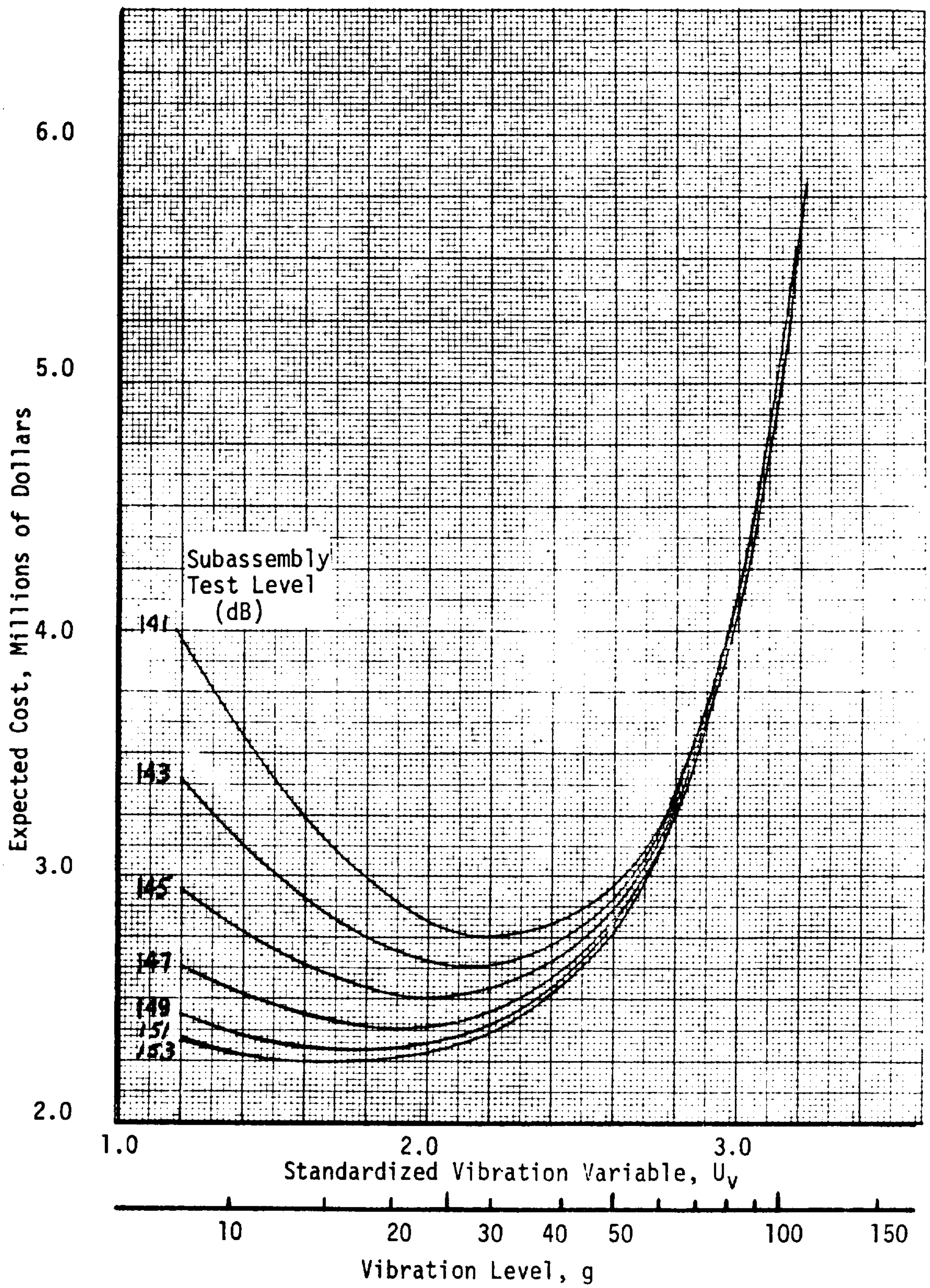


Figure 6-1(b) Test Plan 2 Costs, NEXP=1, NCPE=2

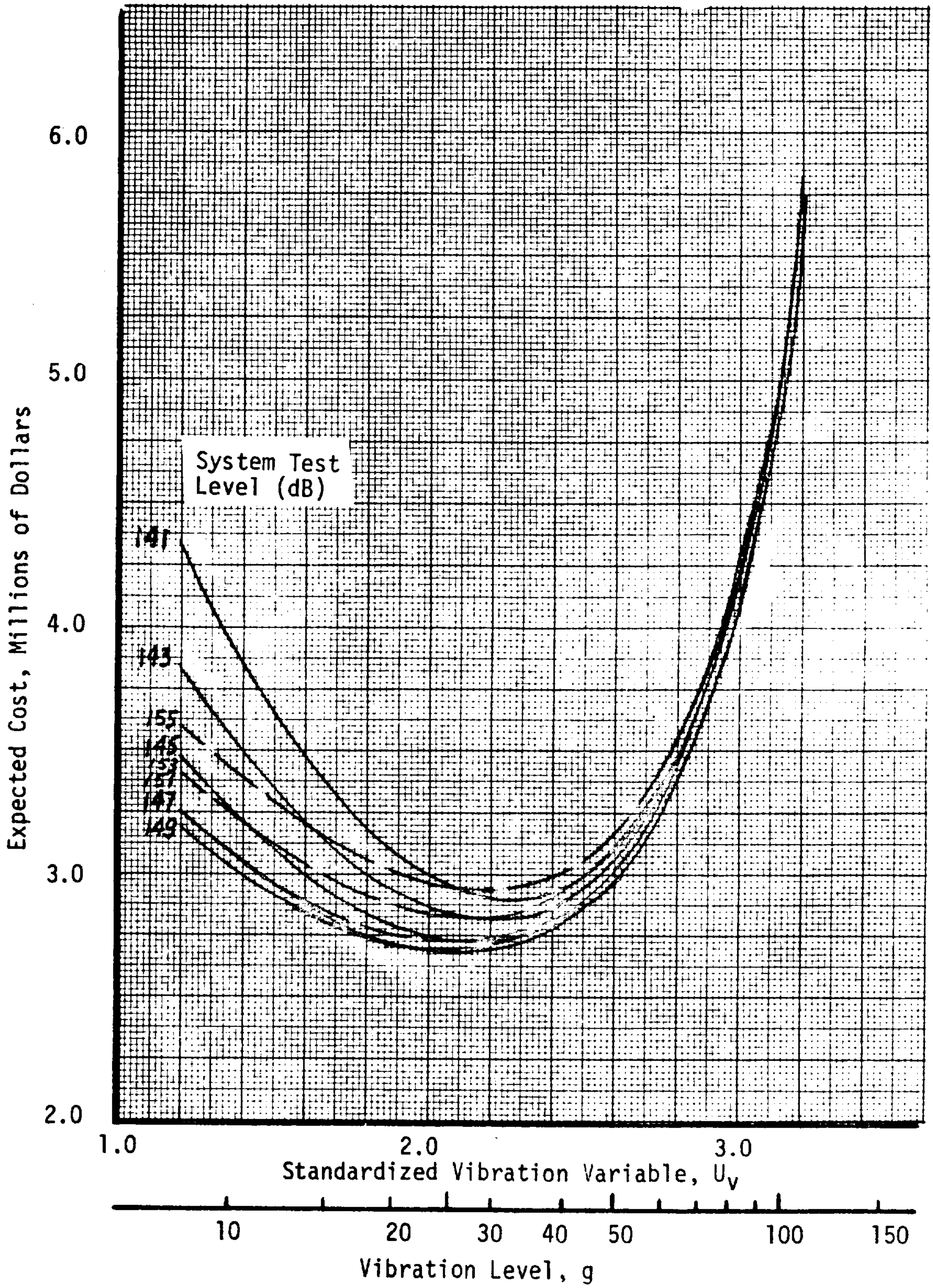


Figure 6-1(c) Test Plan 3 Costs, NEXP=1, NCPE=2

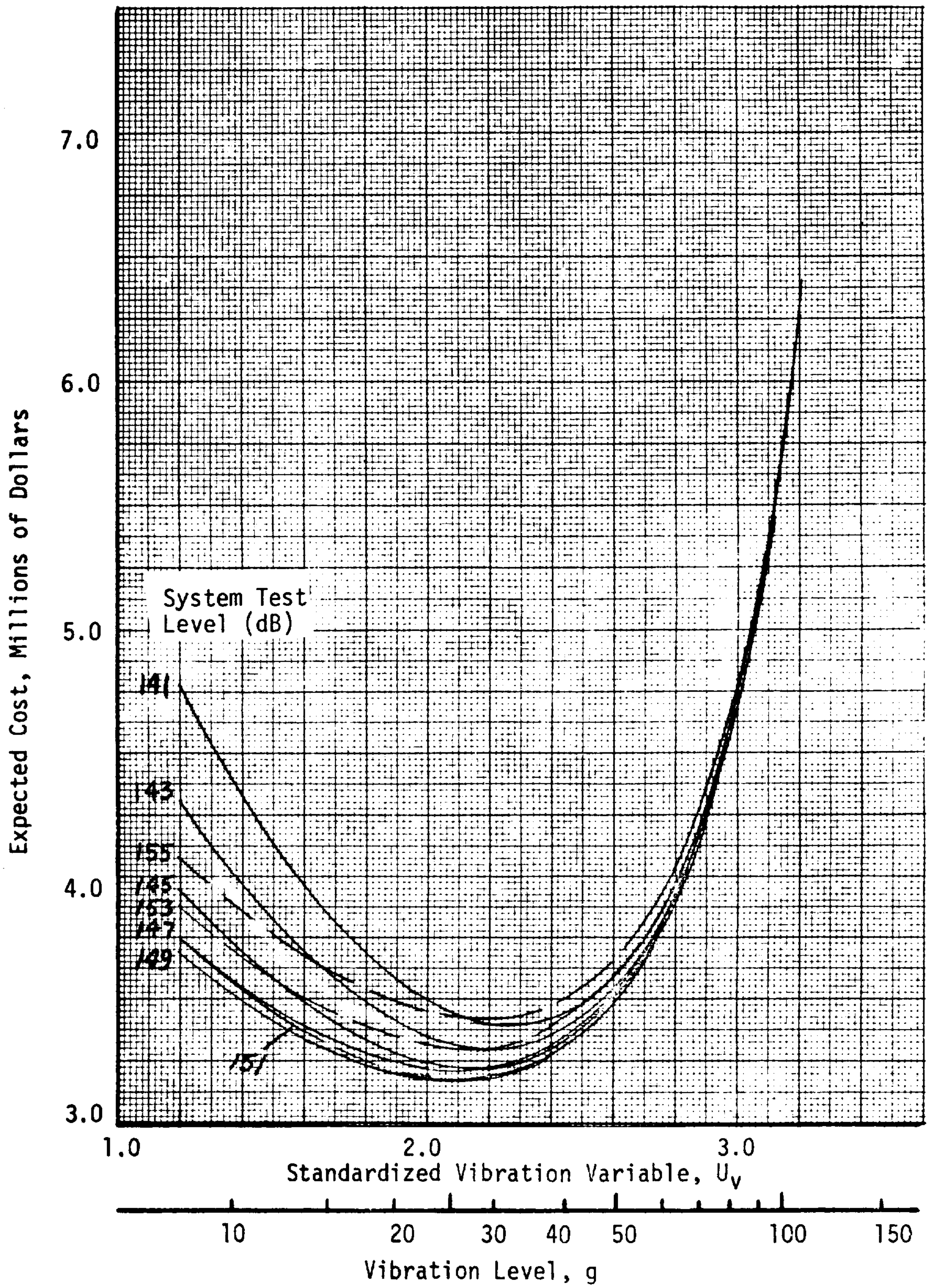


Figure 6-1(d) Test Plan 3A Costs, NEXP=1, NCPE=2

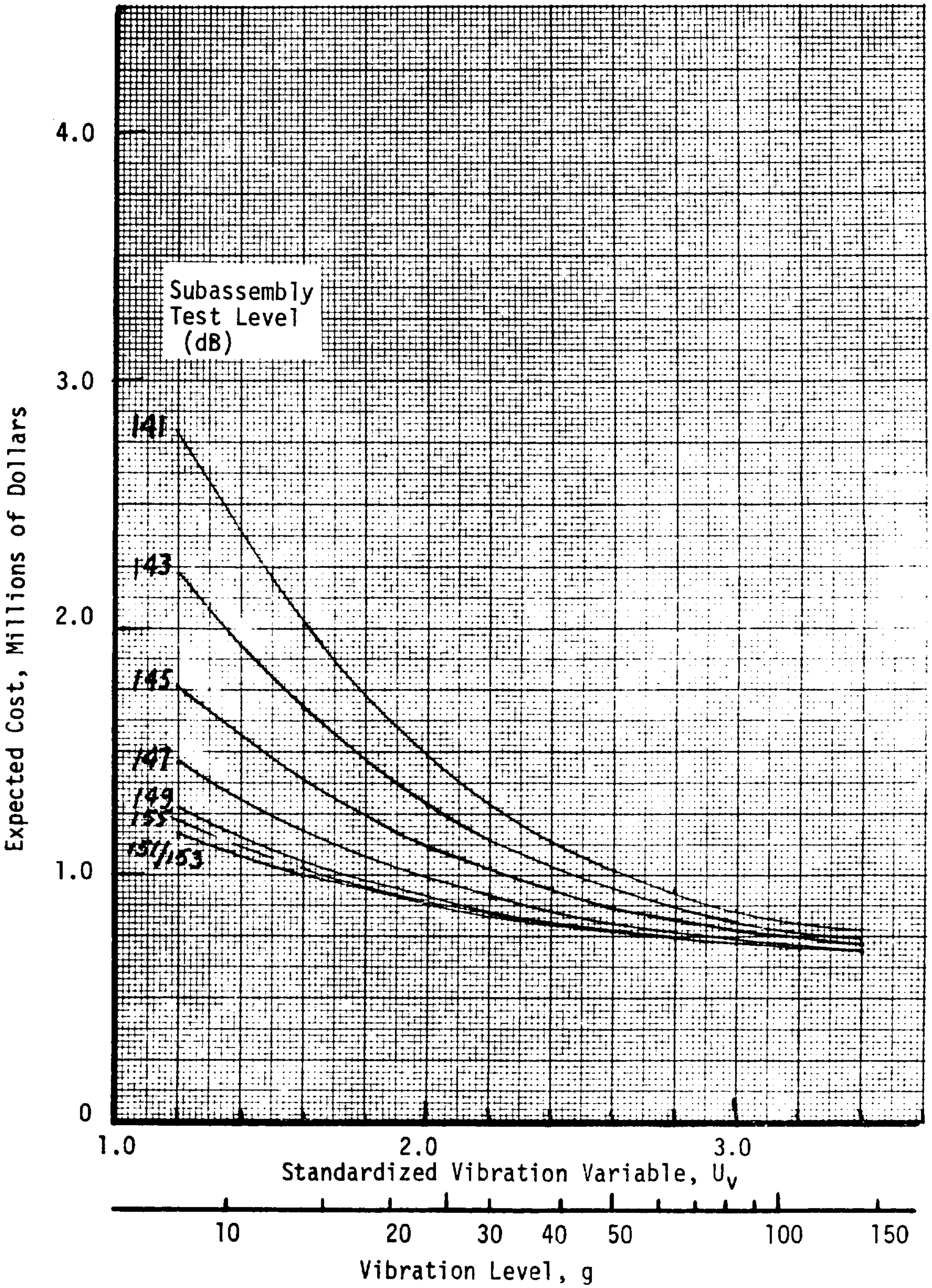


Figure 6-1(e) Test Plan 4 Costs, NEXP=1, NCPE=2

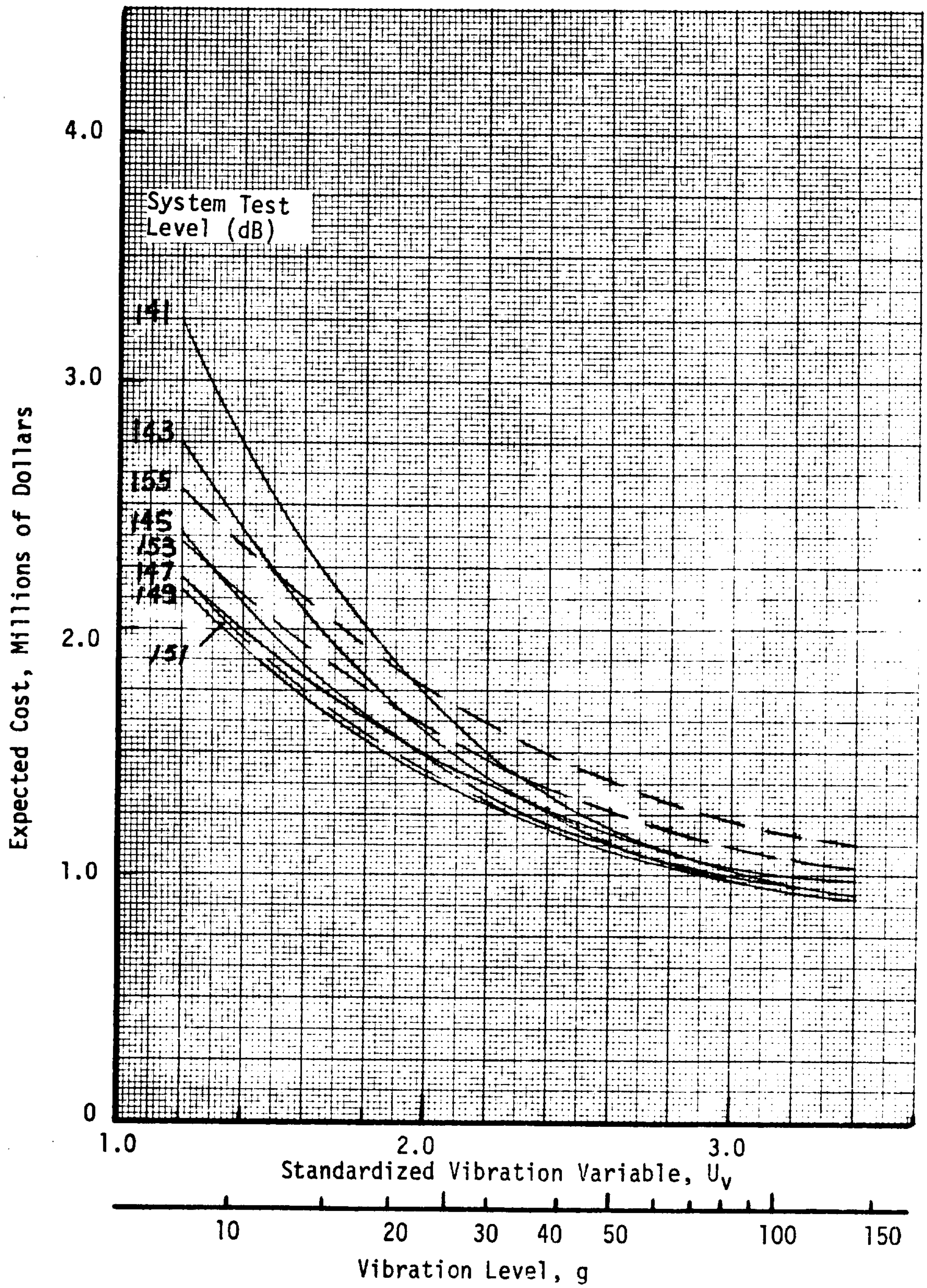


Figure 6-1(f) Test Plan 5 Costs, NEXP=1, NCPE=2

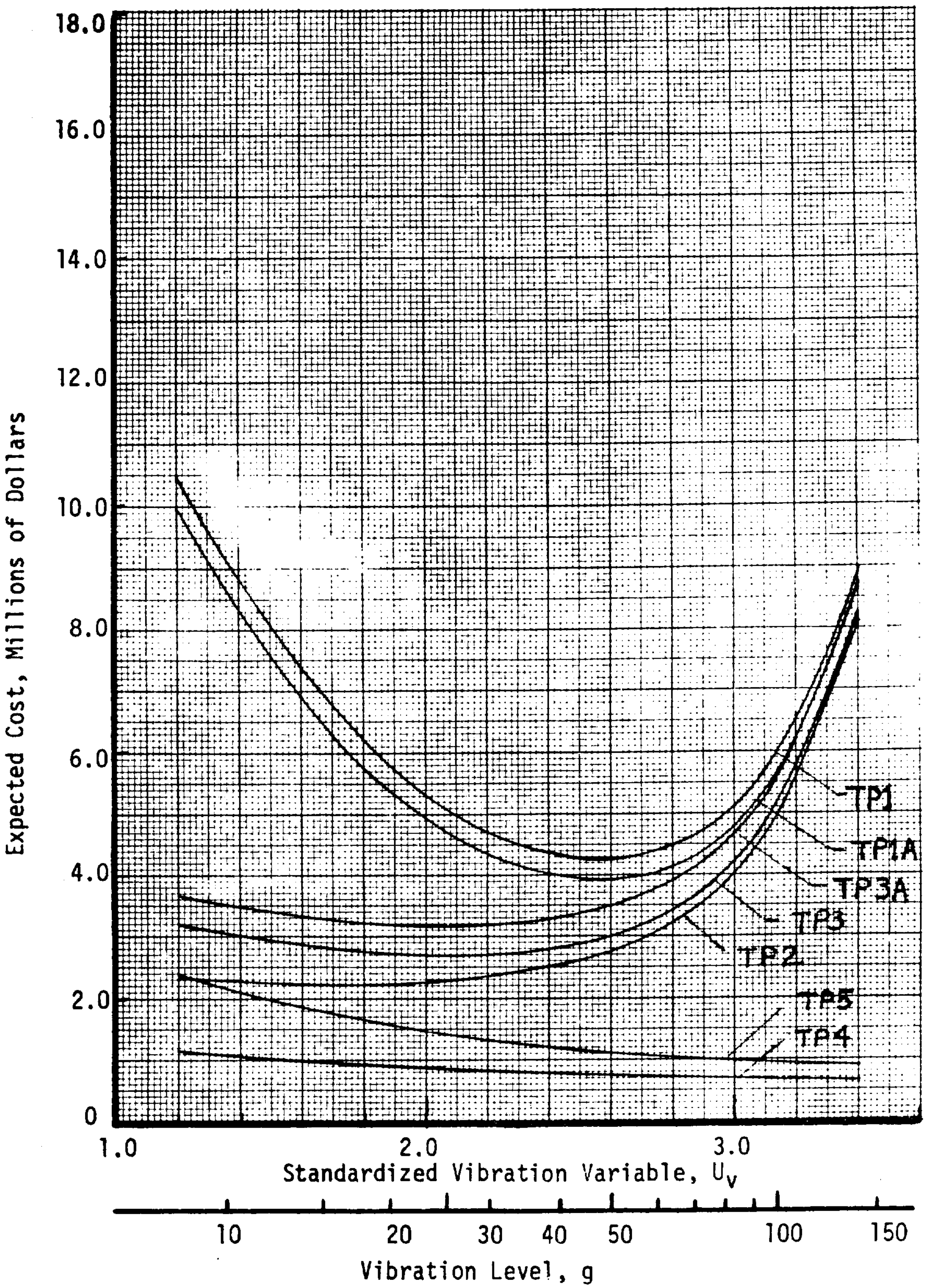


Figure 6-1(g) Optimum Costs for Payload, NEXP=1, NCPE=2

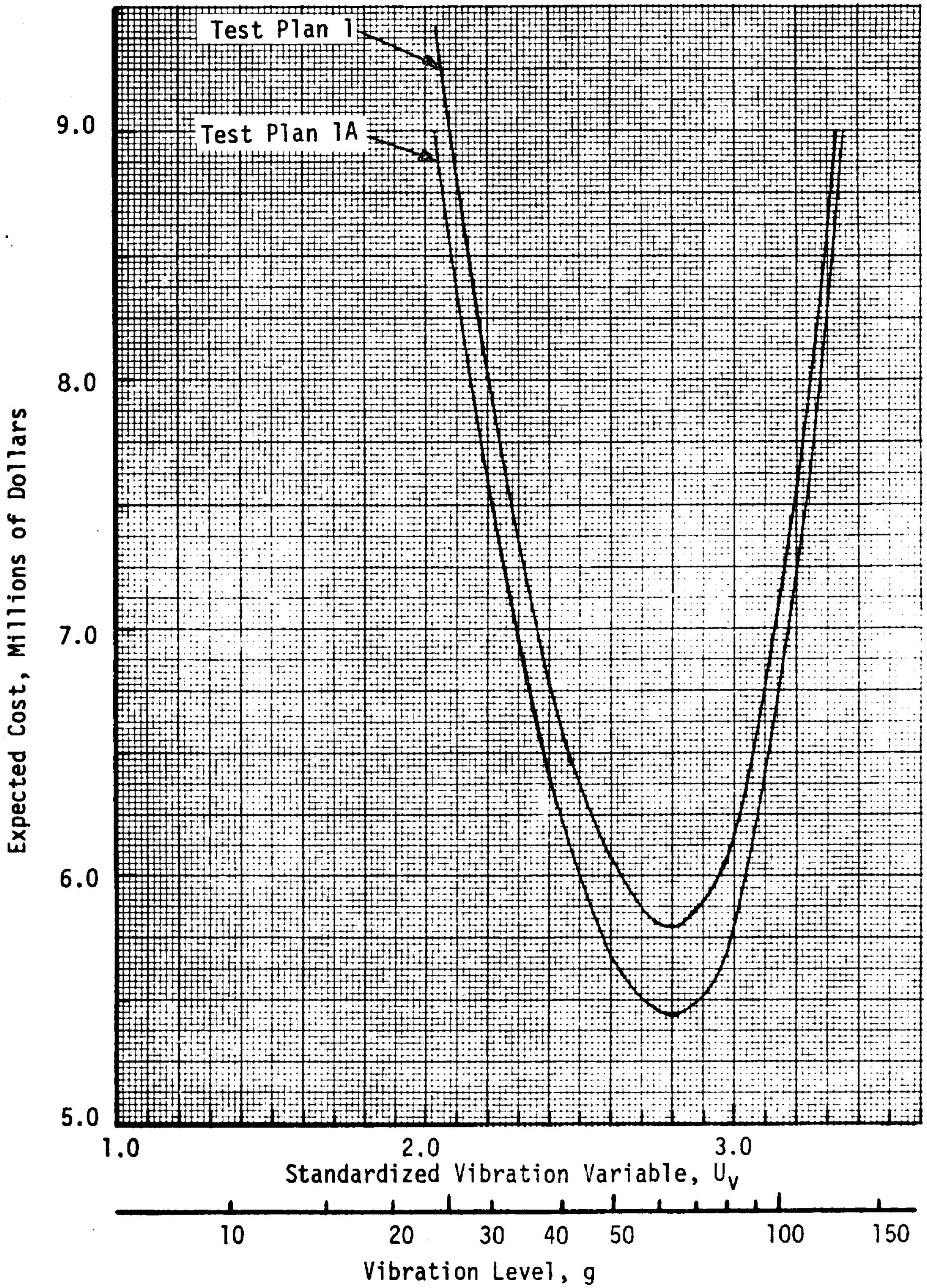


Figure 6-2(a) Test Plans 1 and 1A Costs, NEXP=1, NCPE=6

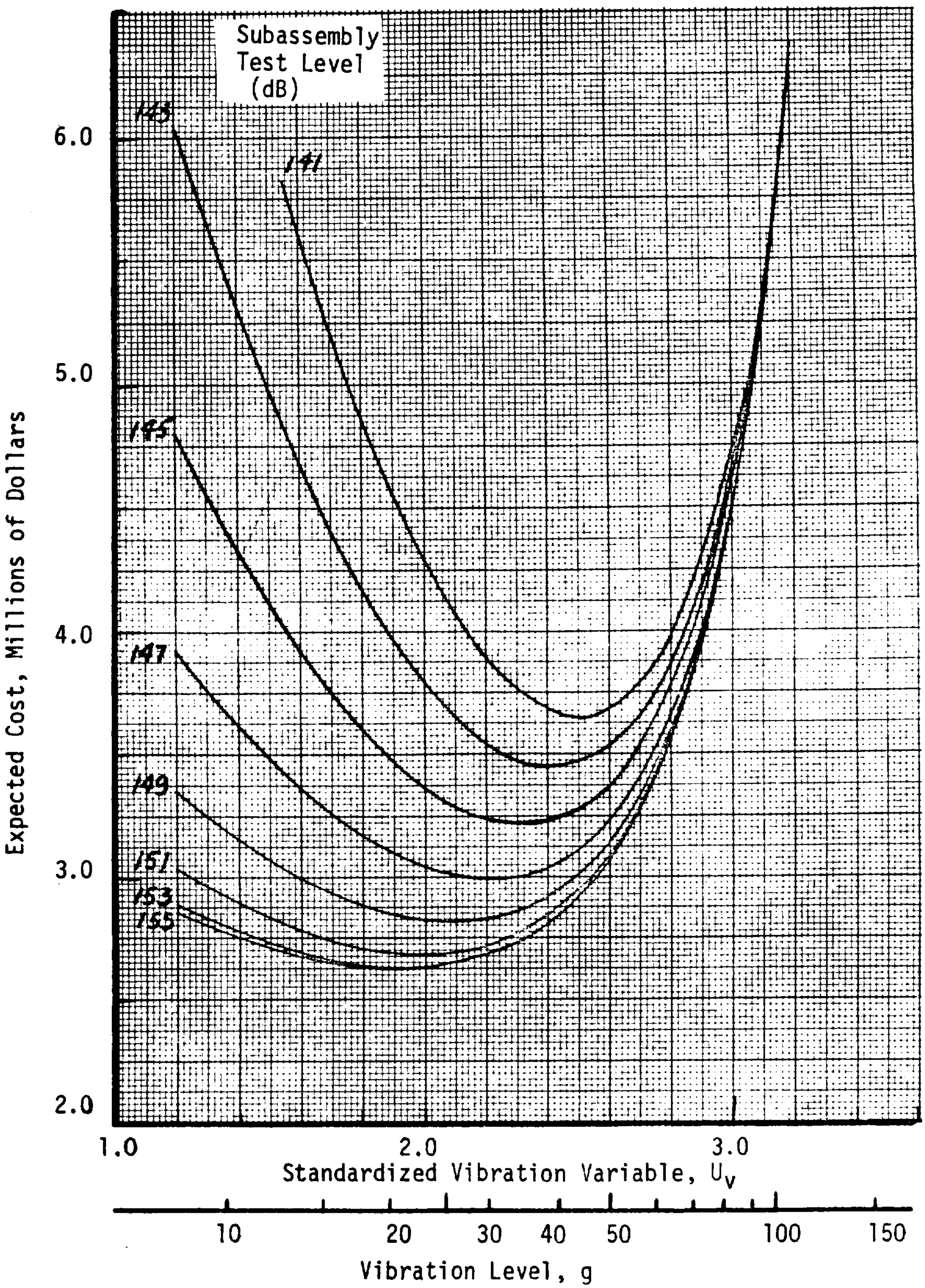


Figure 6-2(b) Test Plan 2 Costs, NEXP=1, NCPE=6

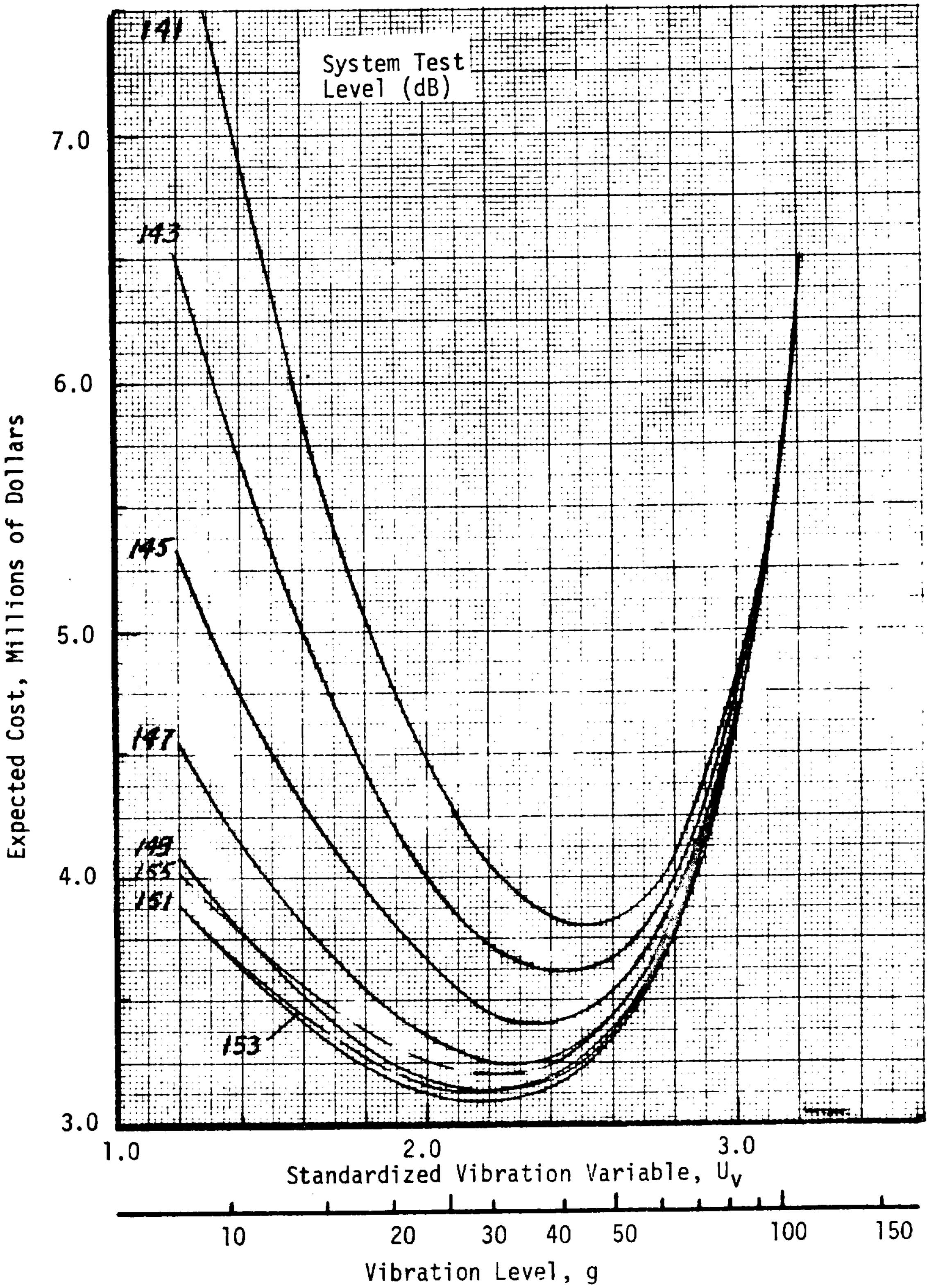


Figure 6-2(c) Test Plan 3 Costs, NEXP=1, NCPE=6

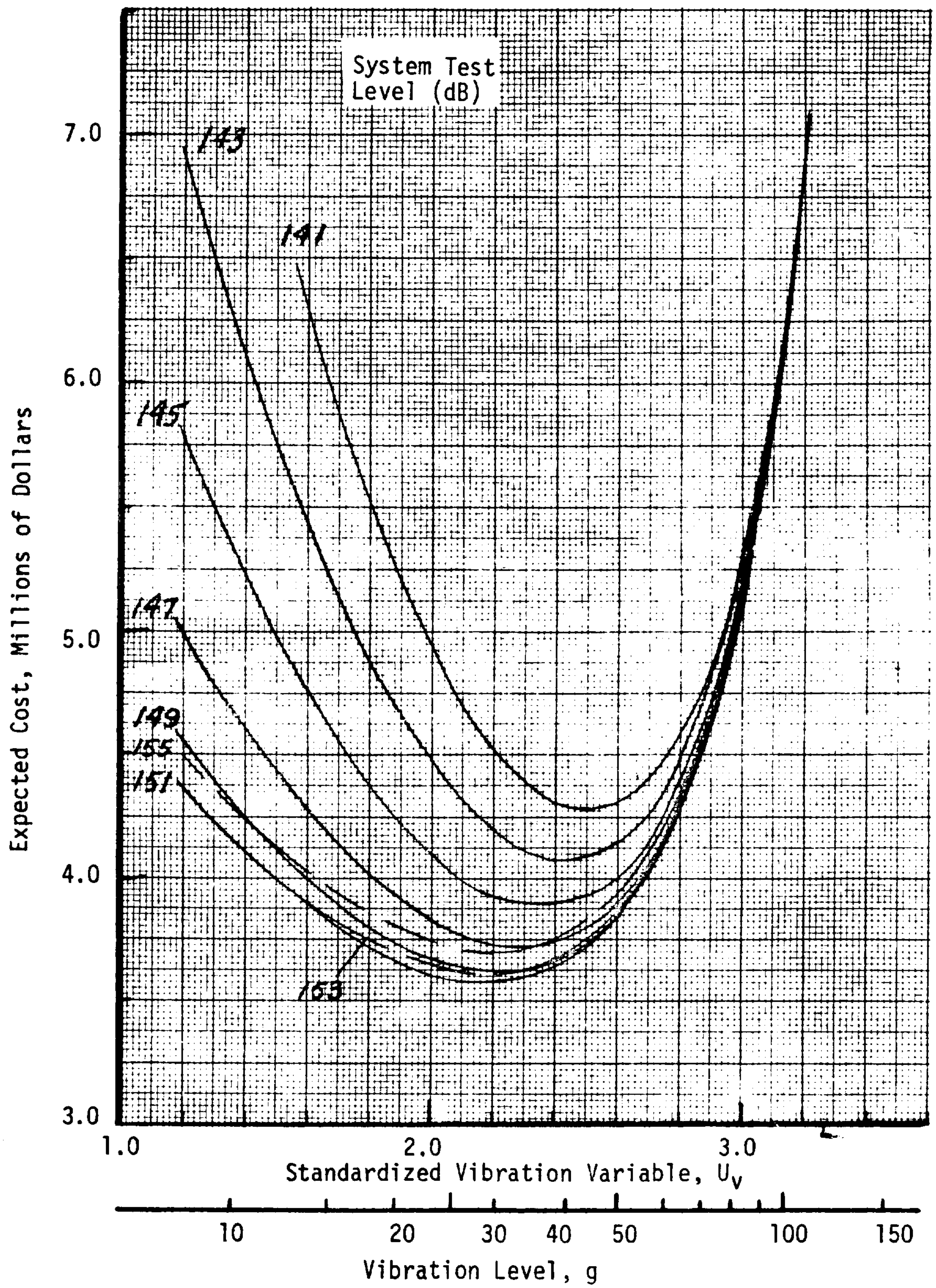


Figure 6-2(d) Test Plan 3A Costs, NEXP=1, NCPE=6

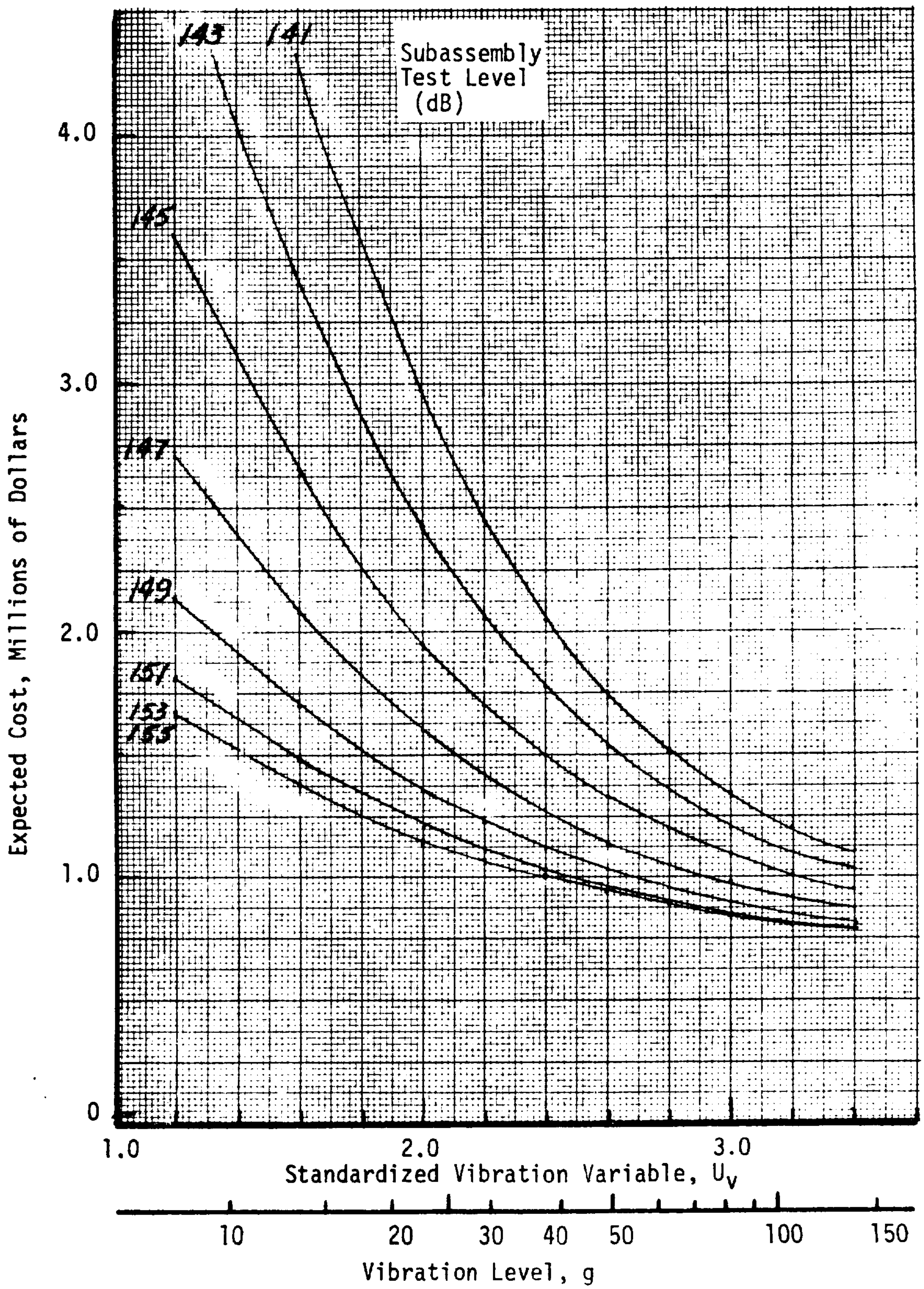


Figure 6-2(e) Test Plan 4 Costs, NEXP=1, NCPE=6

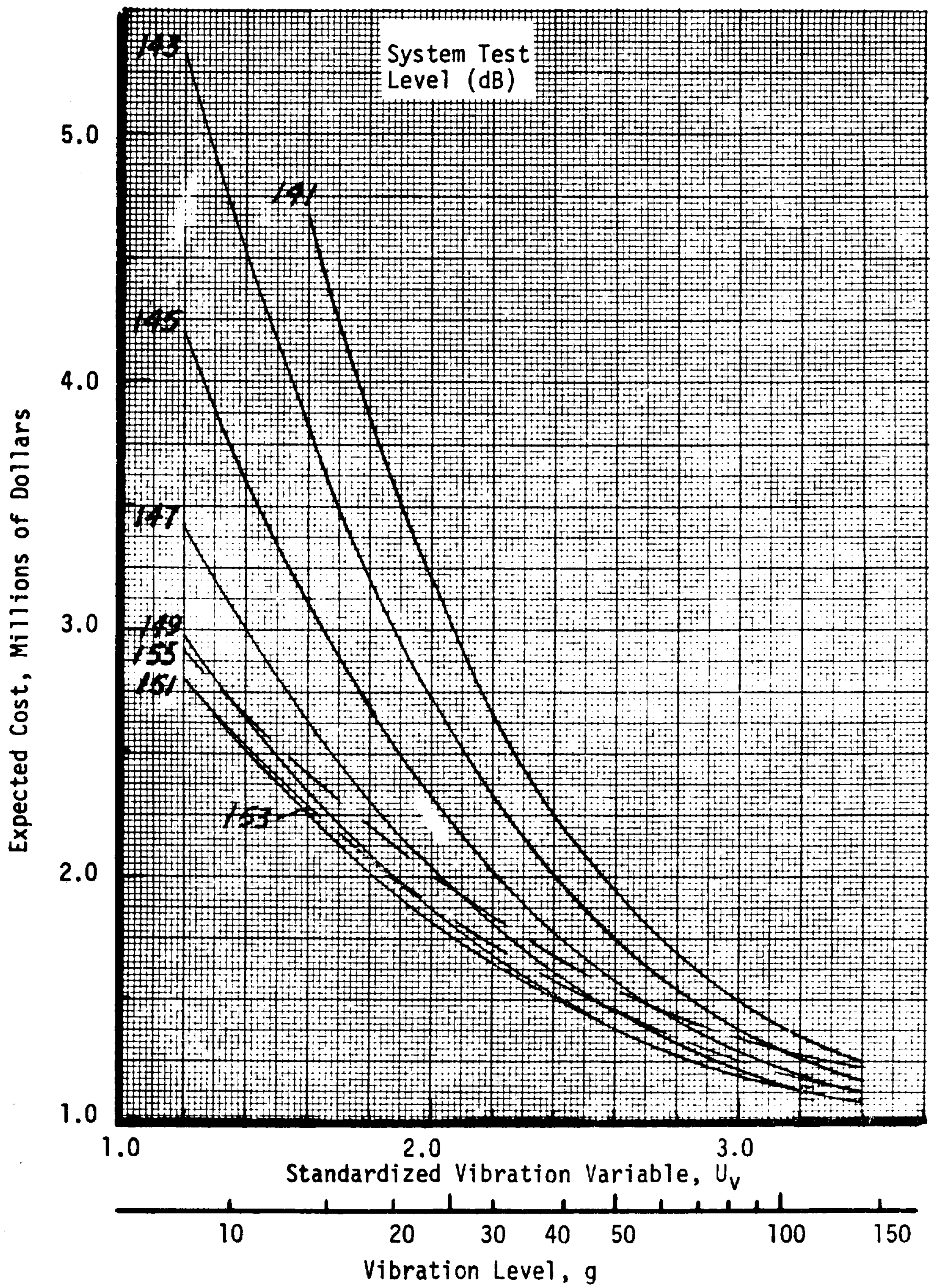


Figure 6-2(f) Test Plan 5 Costs, NEXP=1, NCPE=6

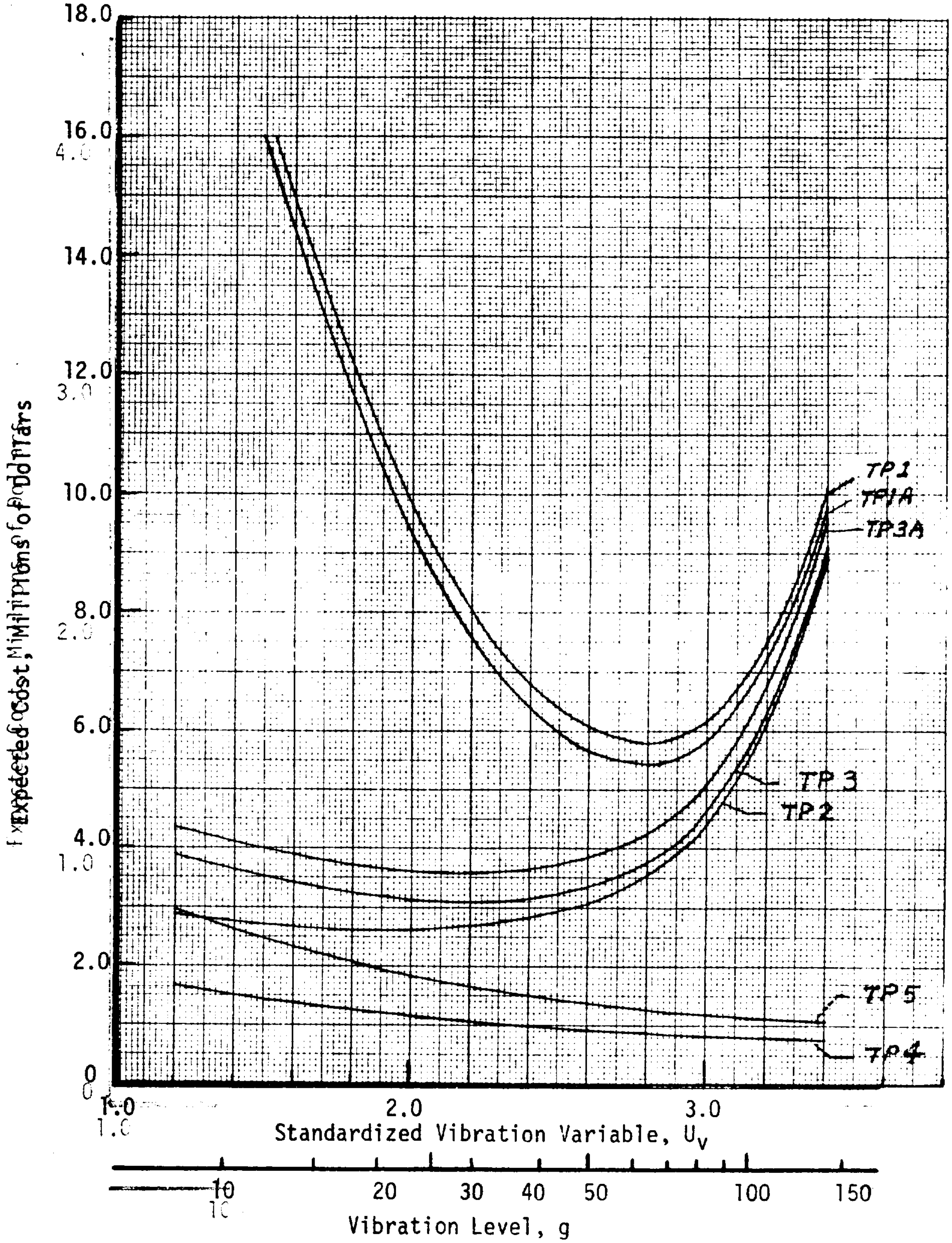


Figure 6-2(g) Optimum Costs for Payload, NEXP=1, NCPE=6

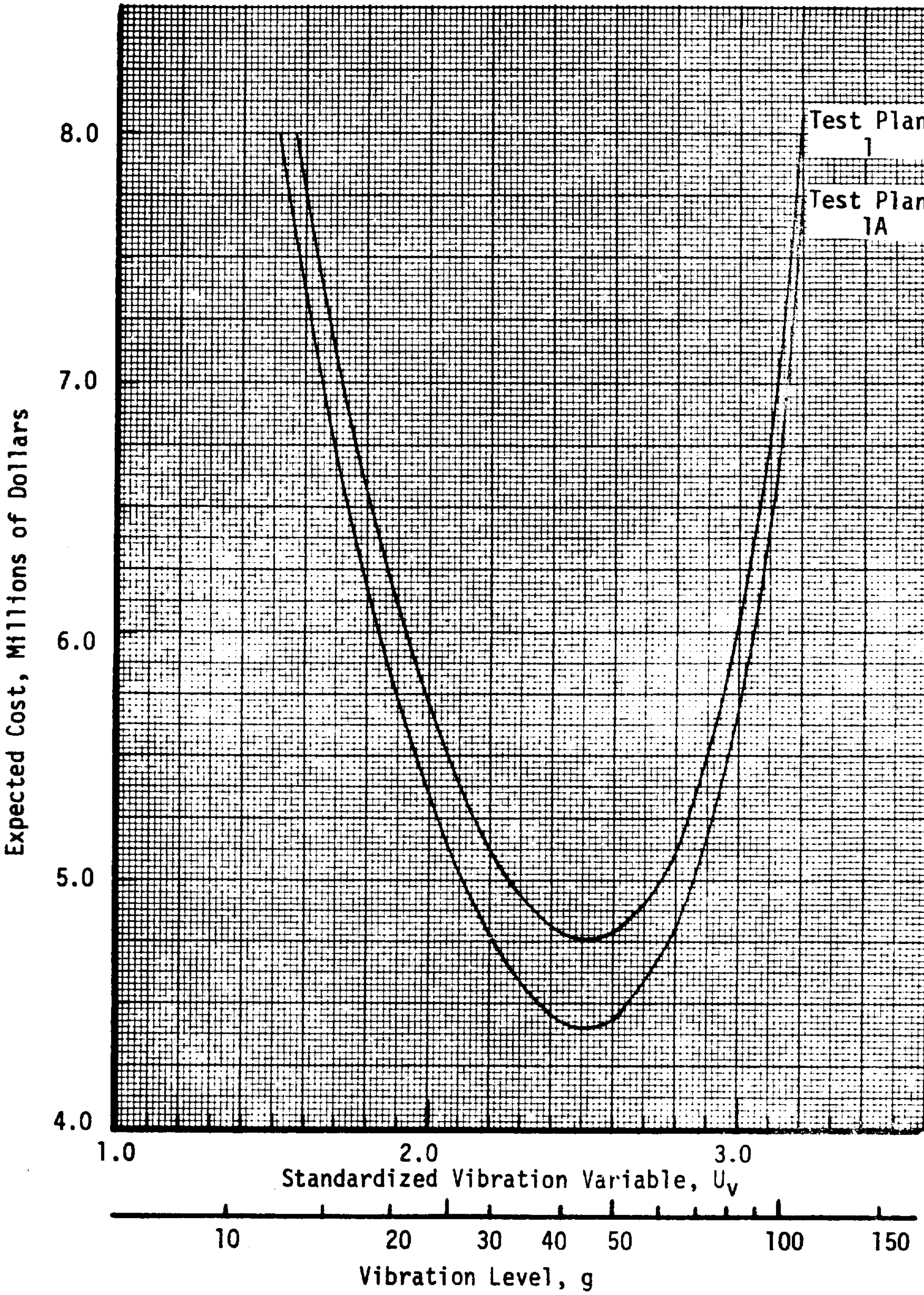


Figure 6-3(a) Test Plans 1 and 1A Costs, NEXP=1, NCPE=2

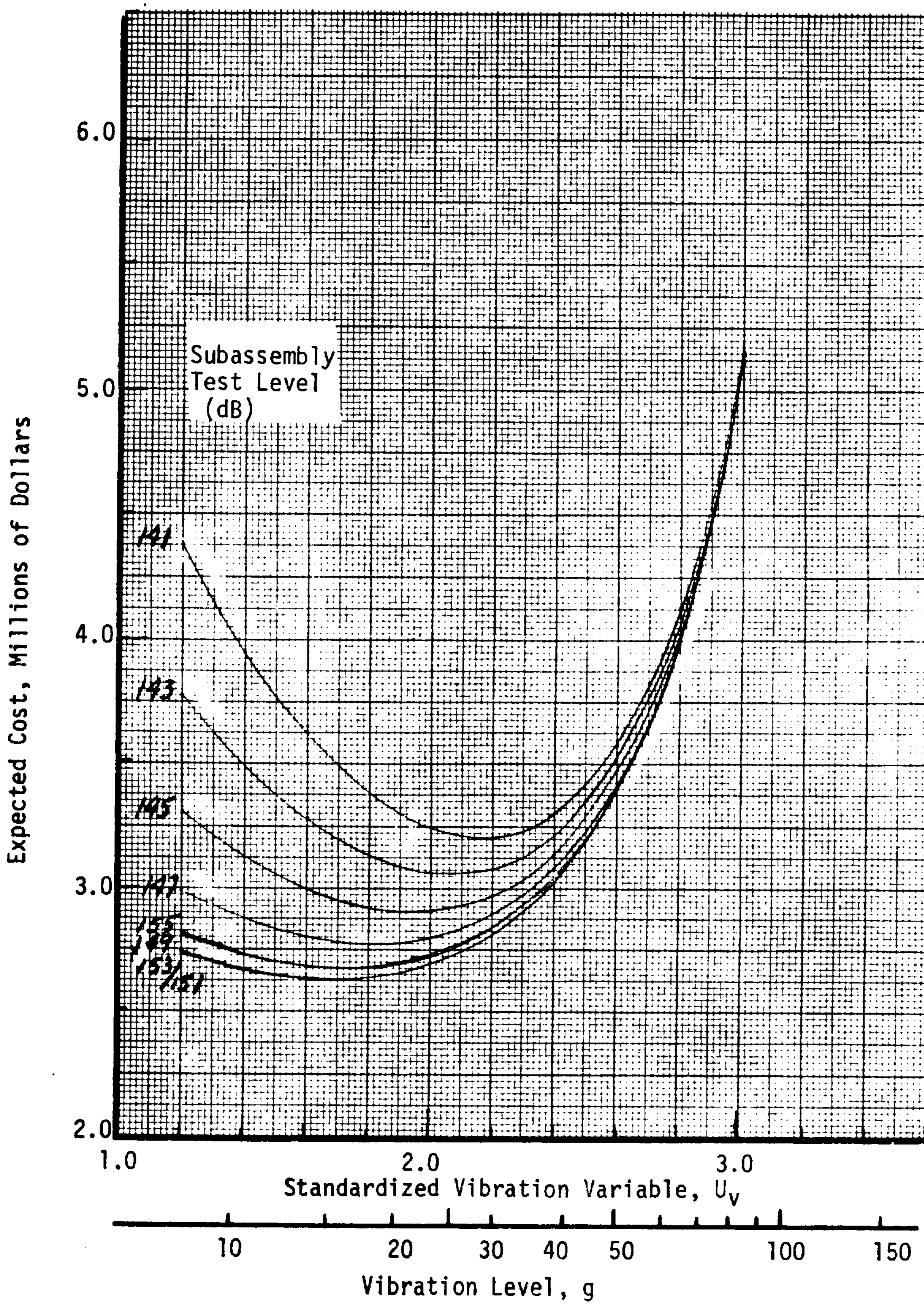


Figure 6-3(b) Test Plan 2 Costs, NEXP=7, NCPE=2

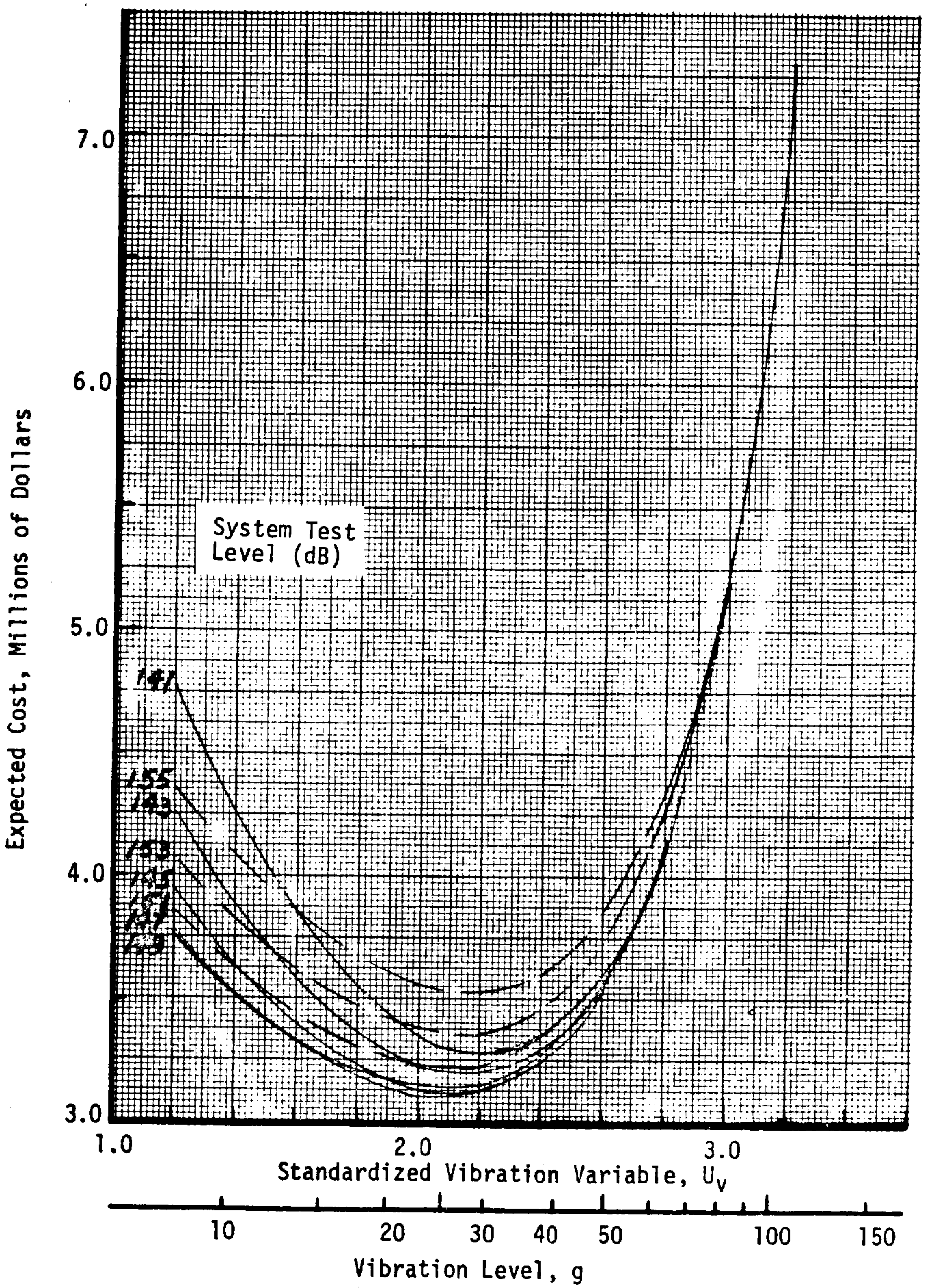


Figure 6-3(c) Test Plan 3 Costs, NEXP=7, NCPE=2

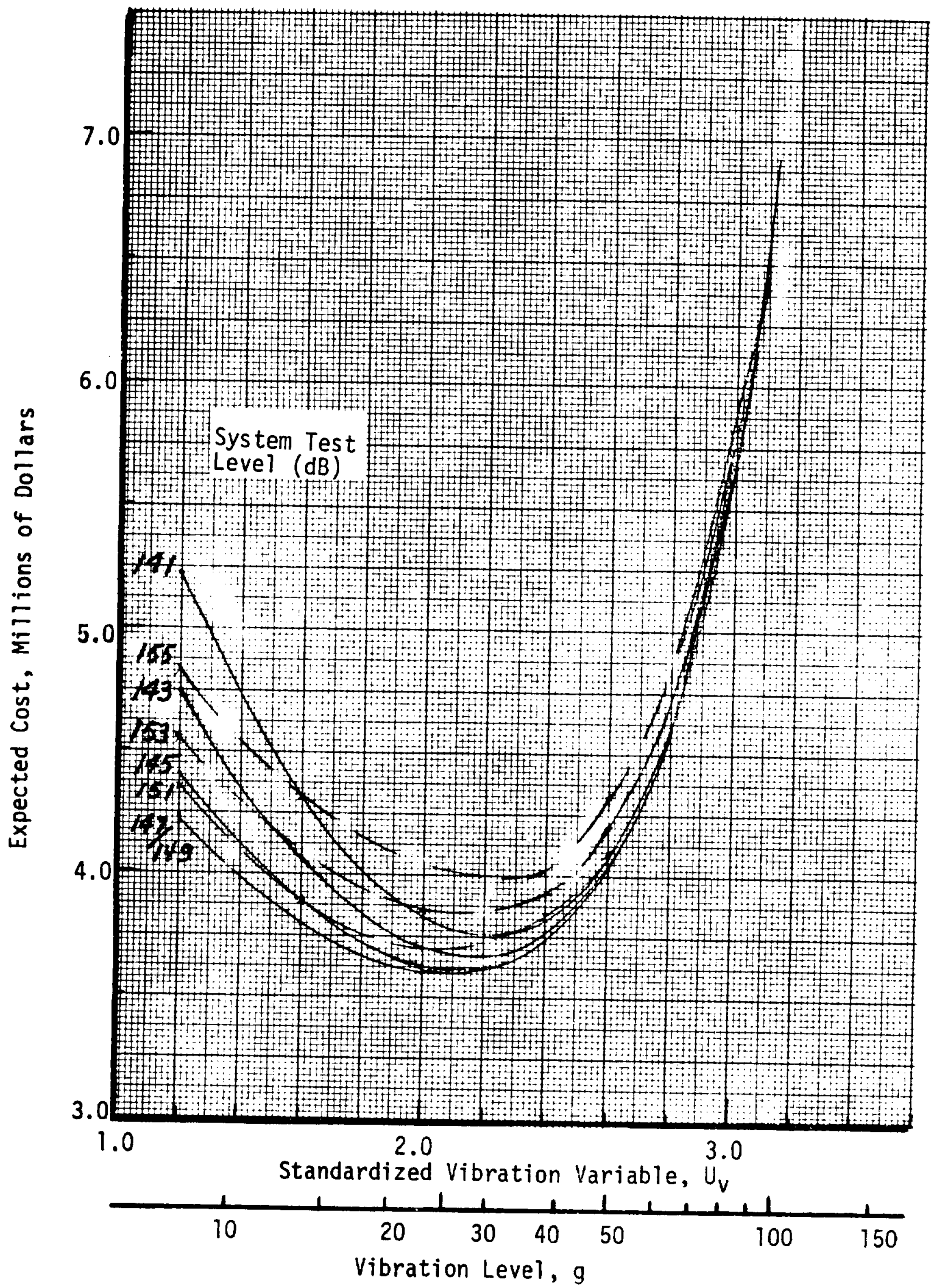
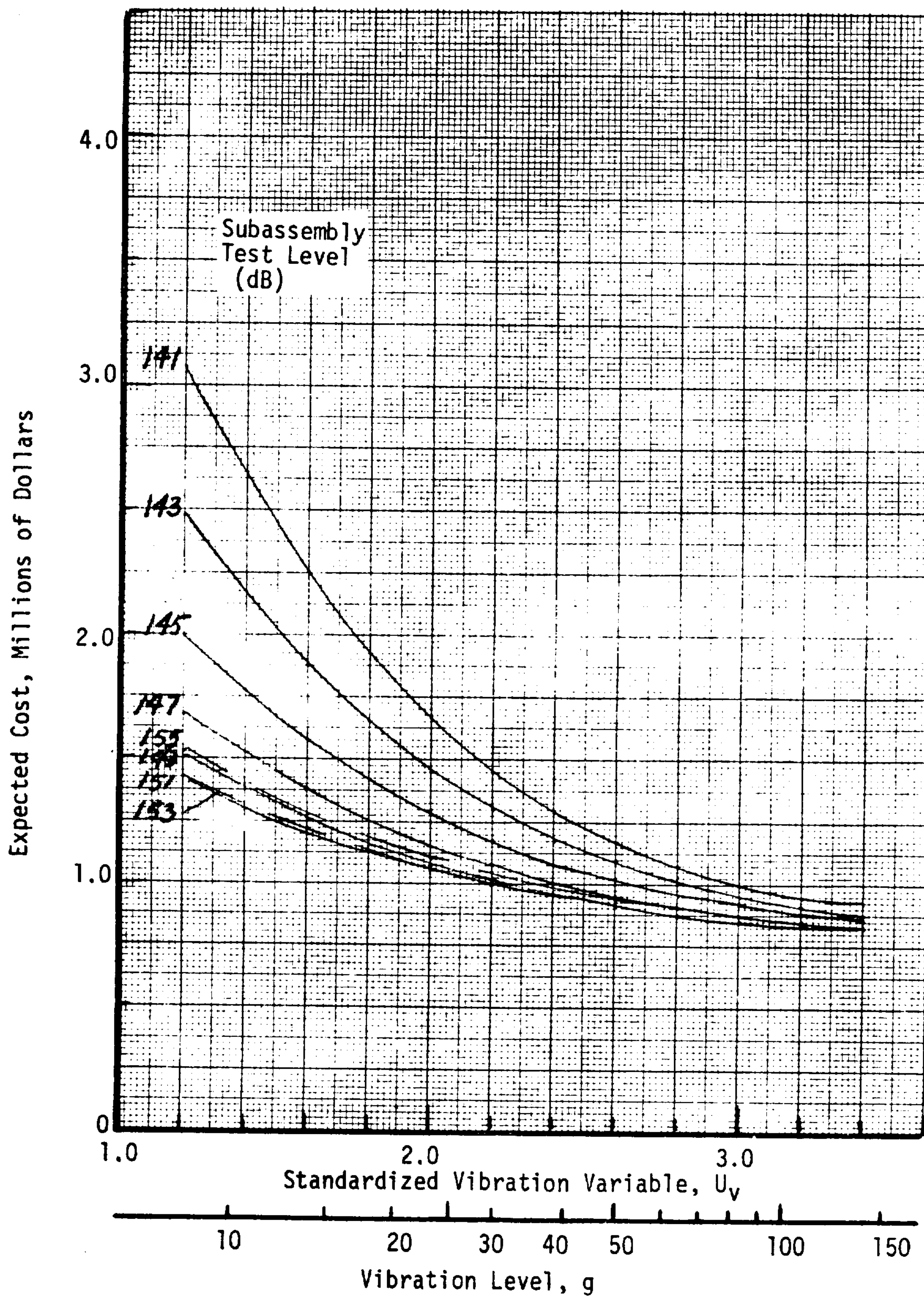


Figure 6-3(d) Test Plan 3A Costs, NEXP=7, NCPE=2



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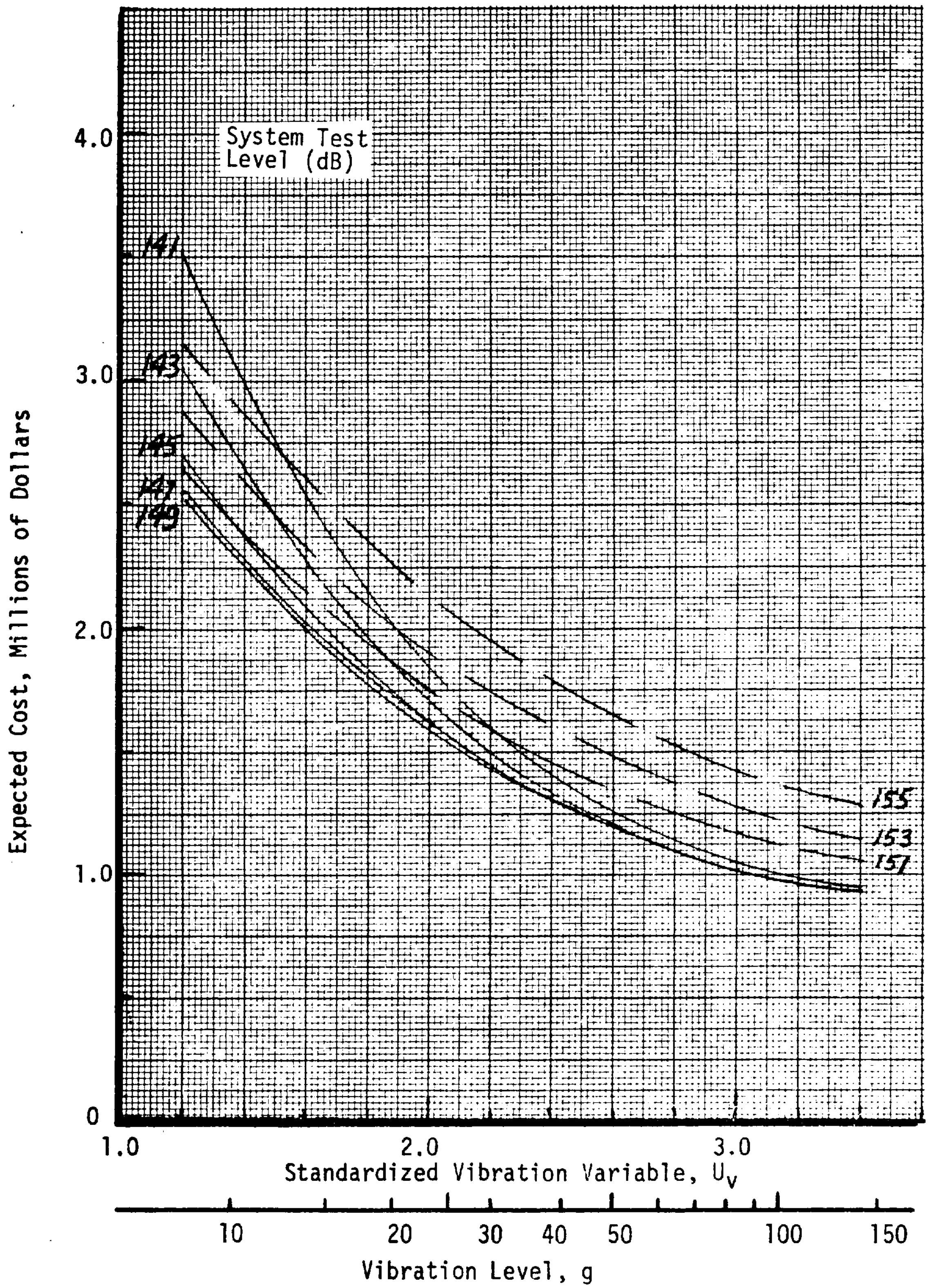


Figure 6-3(f) Test Plan 5 Costs, NEXP=7, NCPE=2

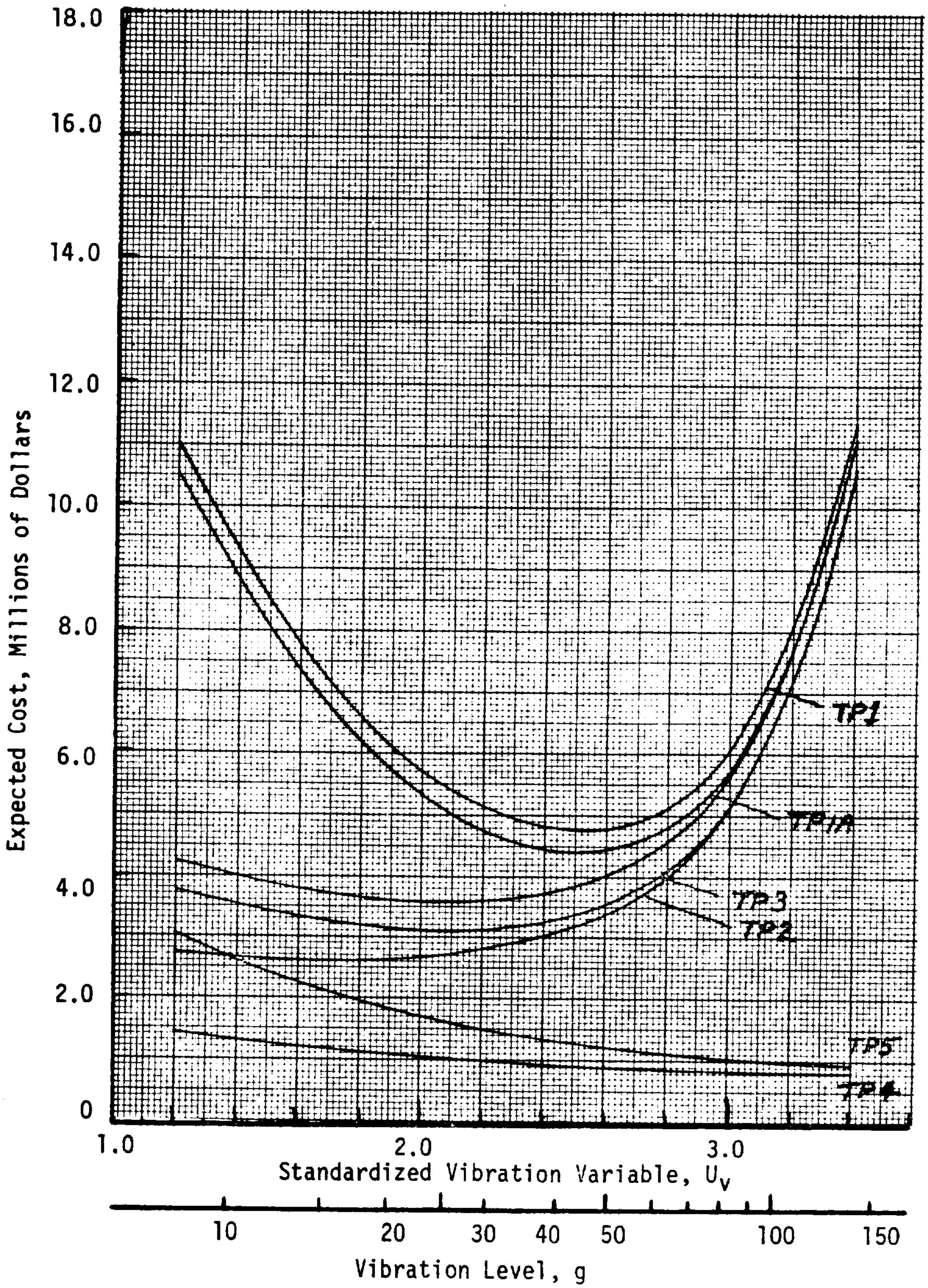


Figure 6-3(g) Optimum Costs for Payload, NEXP=7, NCPE=2

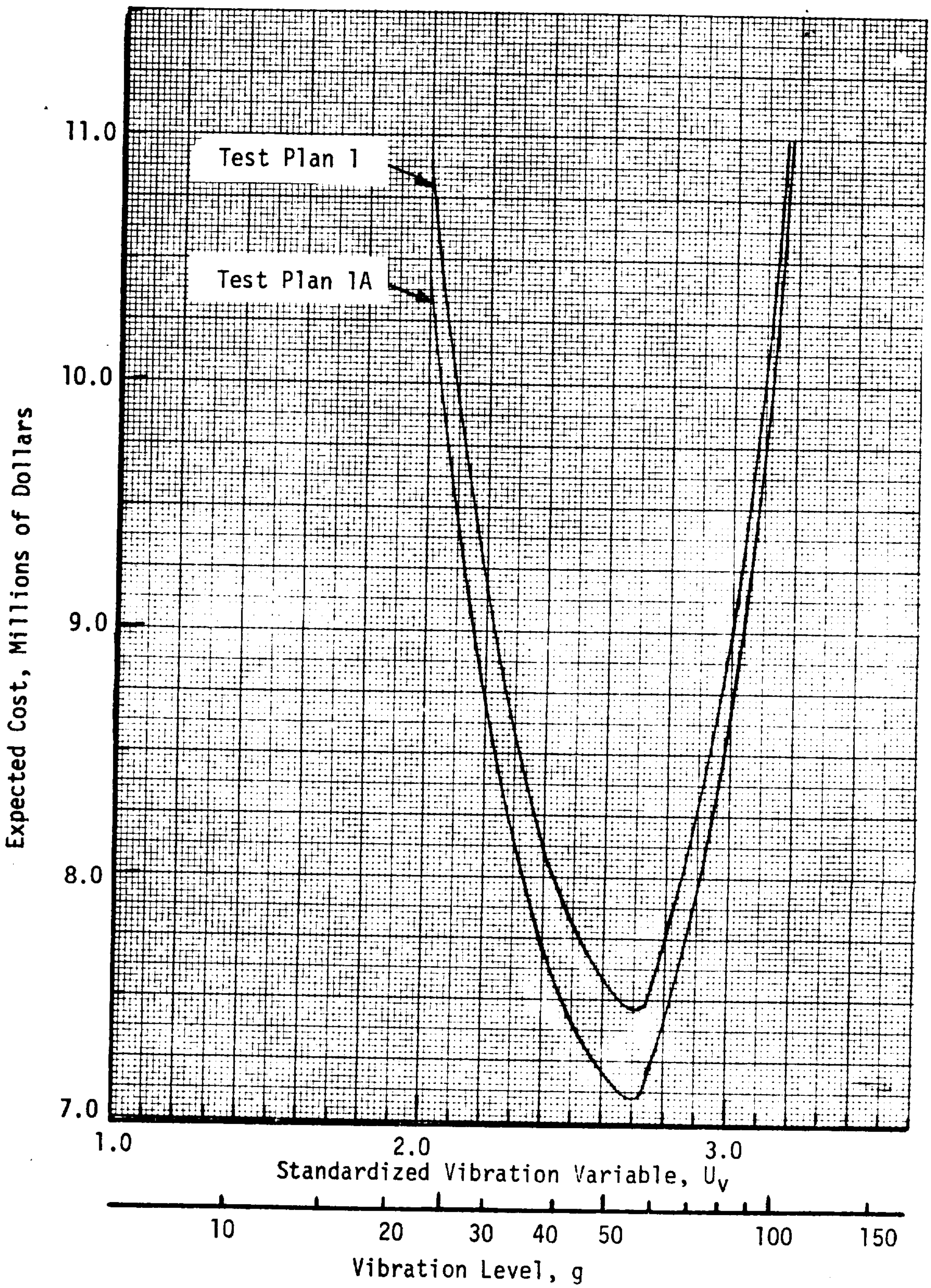


Figure 6-4(a) Test Plans 1 and 1A Costs, NEXP=7, NCPE=6

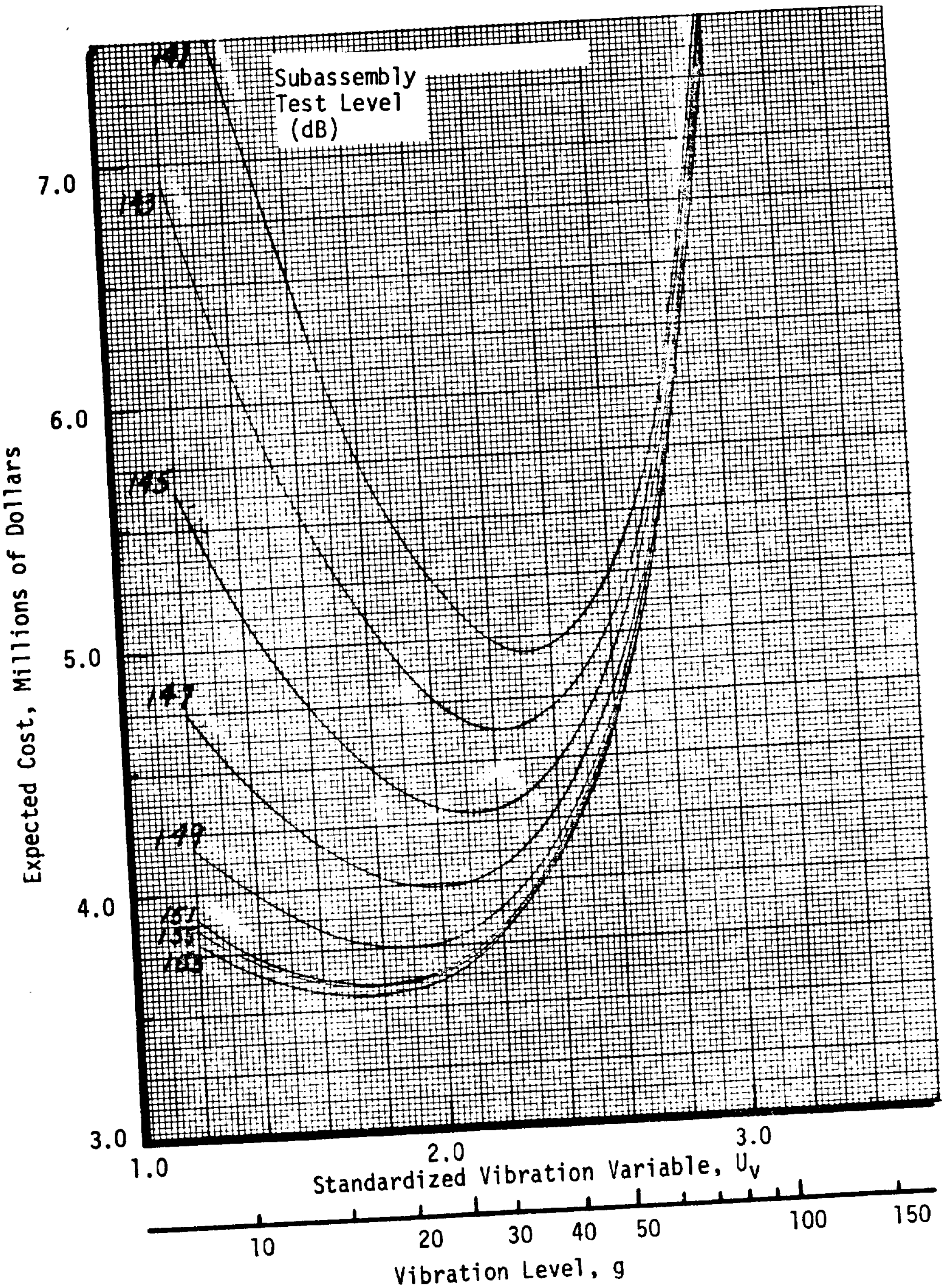
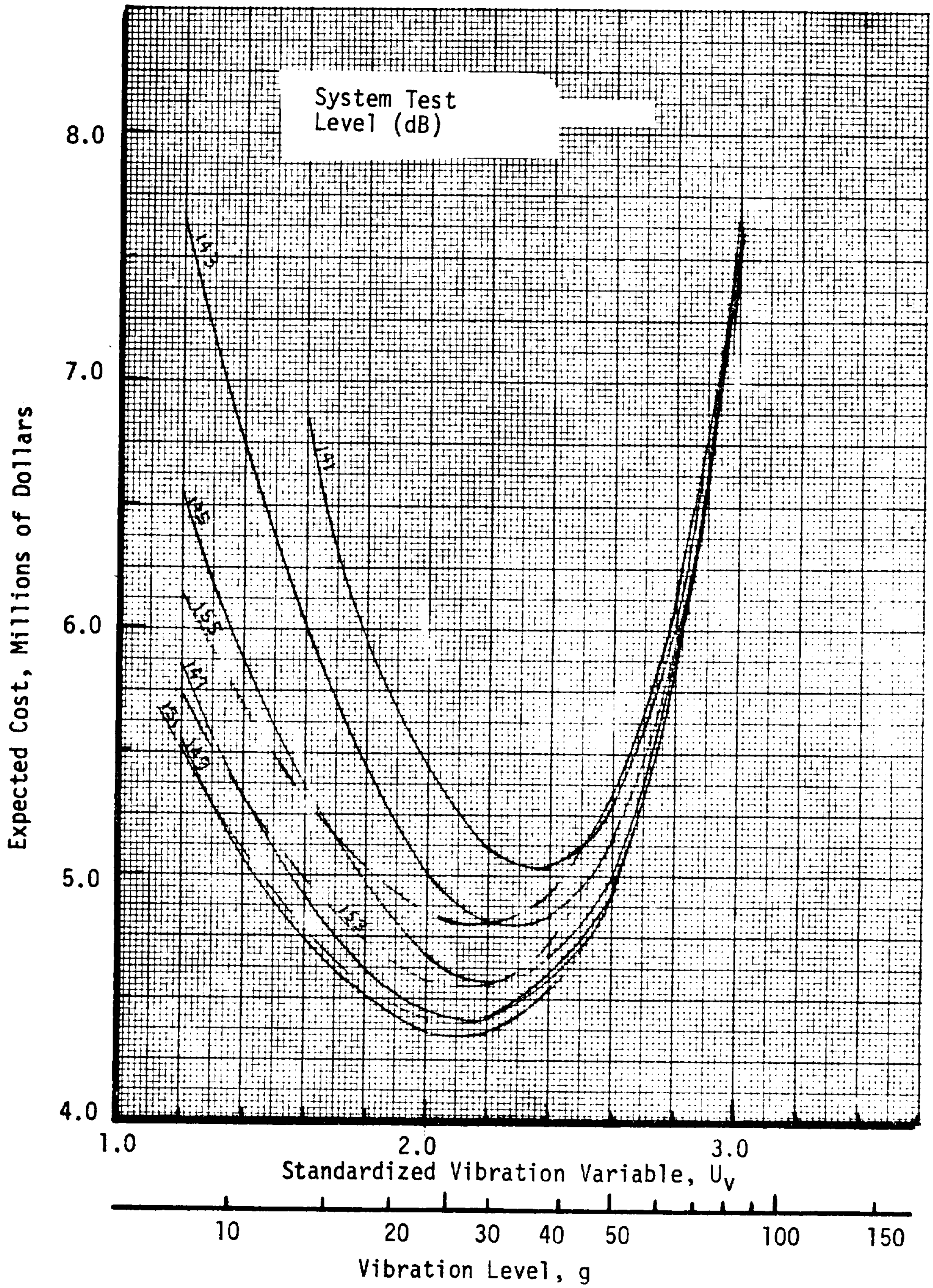


Figure 6-4(b) Test Plan 2 Costs, NEXP=7, NCPE=6



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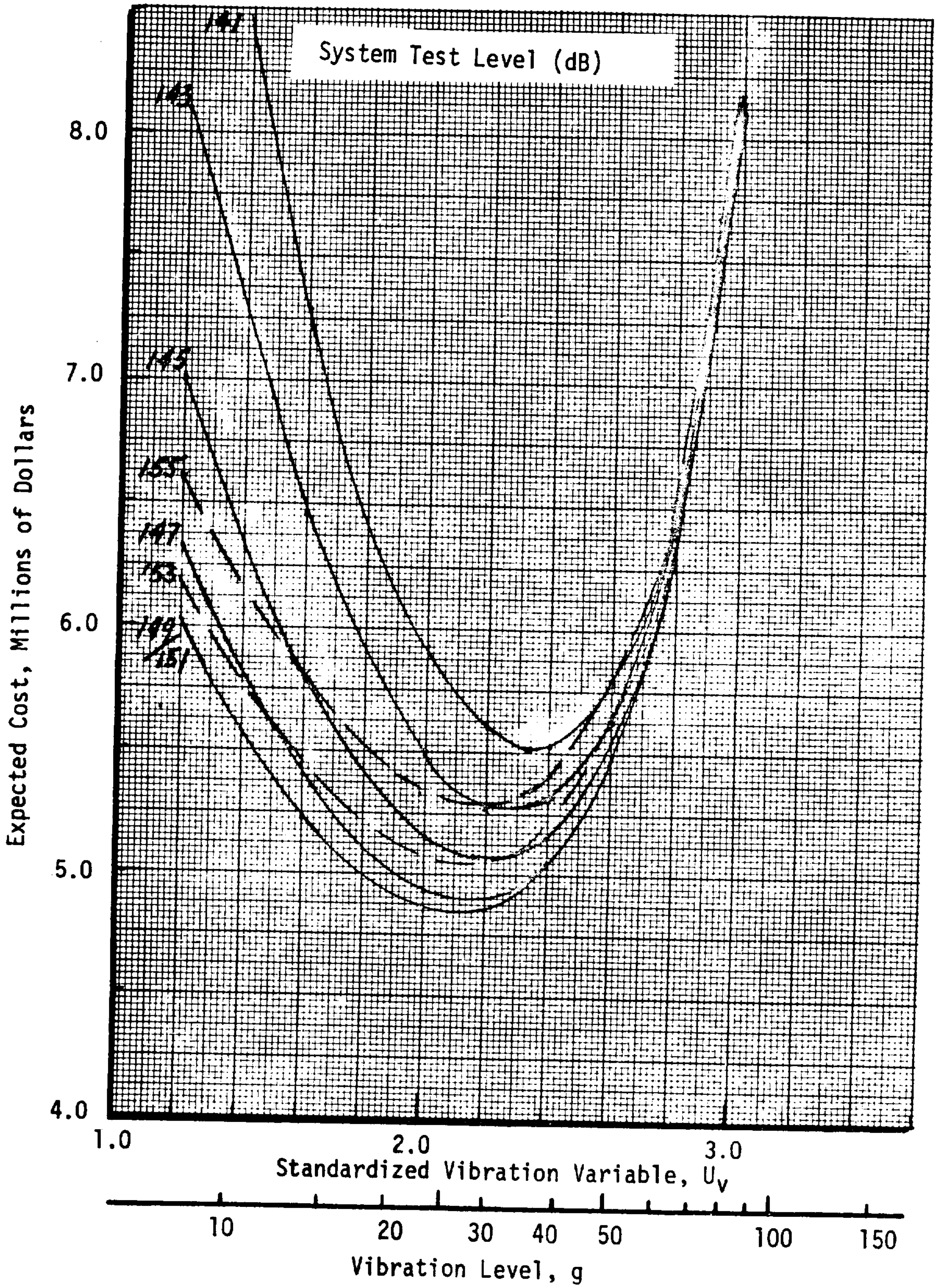

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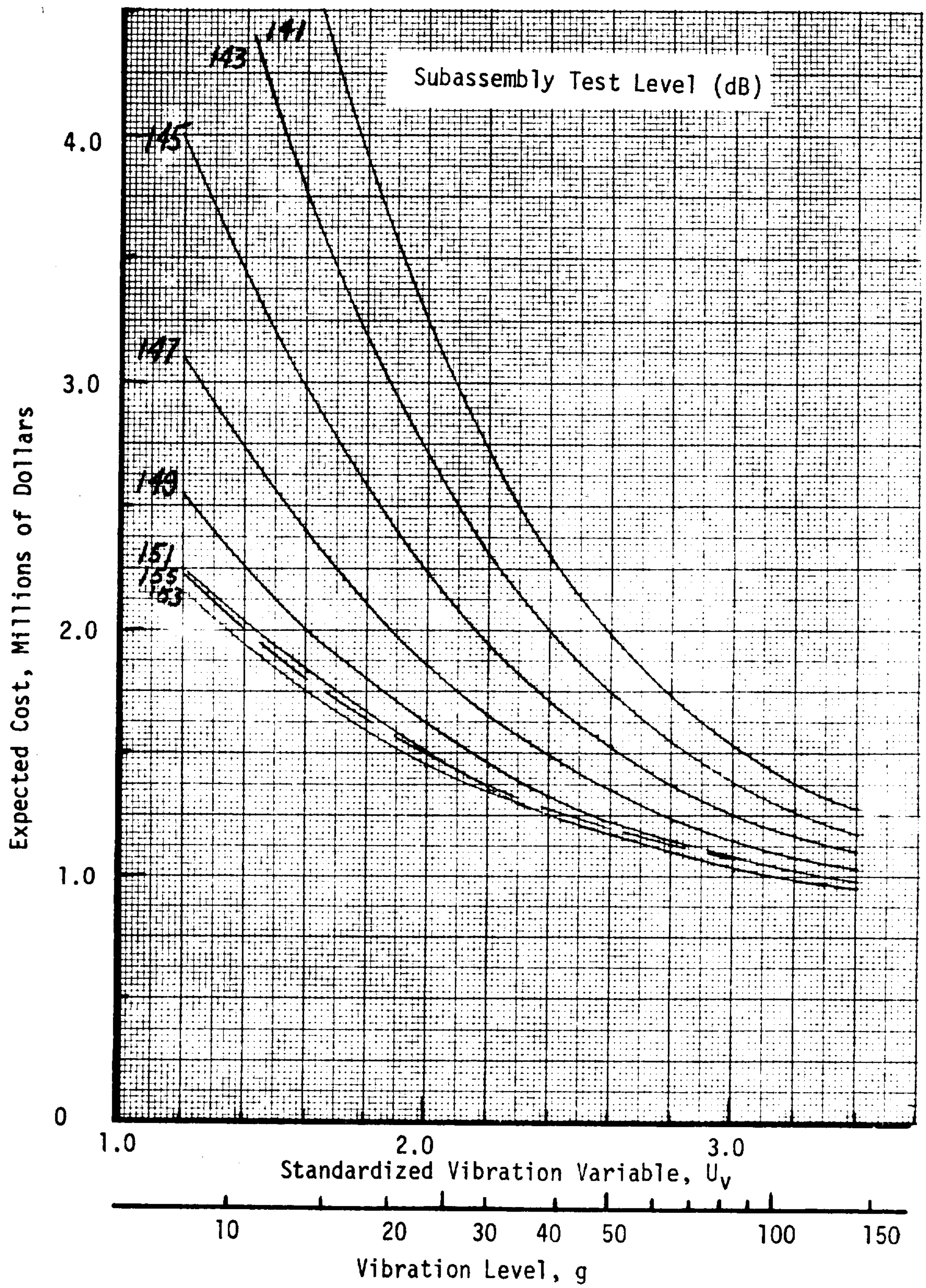

Figure 6-4(e) Test Plan 4 Costs, NEXP=7, NCPE=6

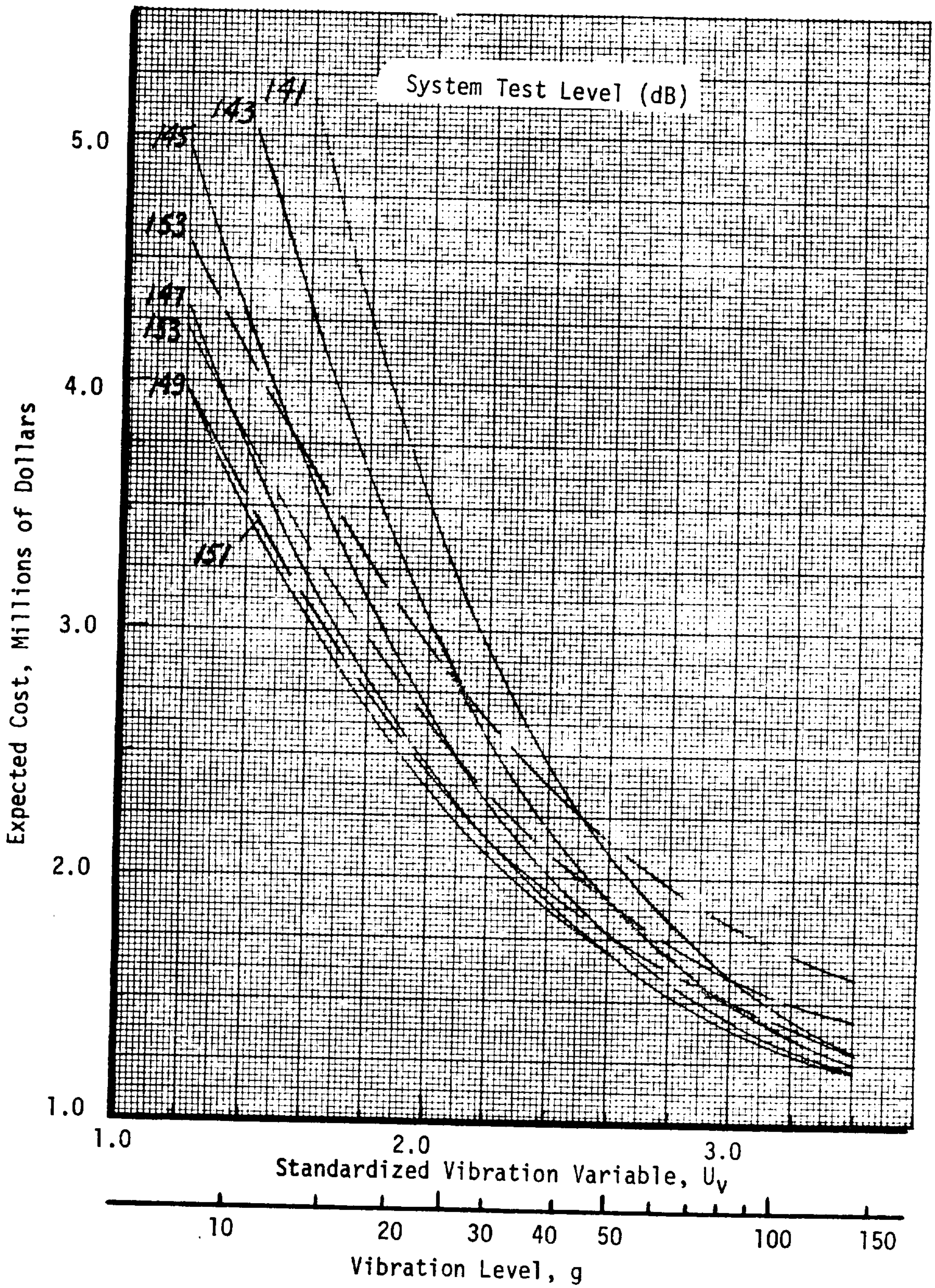

Figure 6-4(f) Test Plan 5 Costs, NEXP=7, NCPE=6

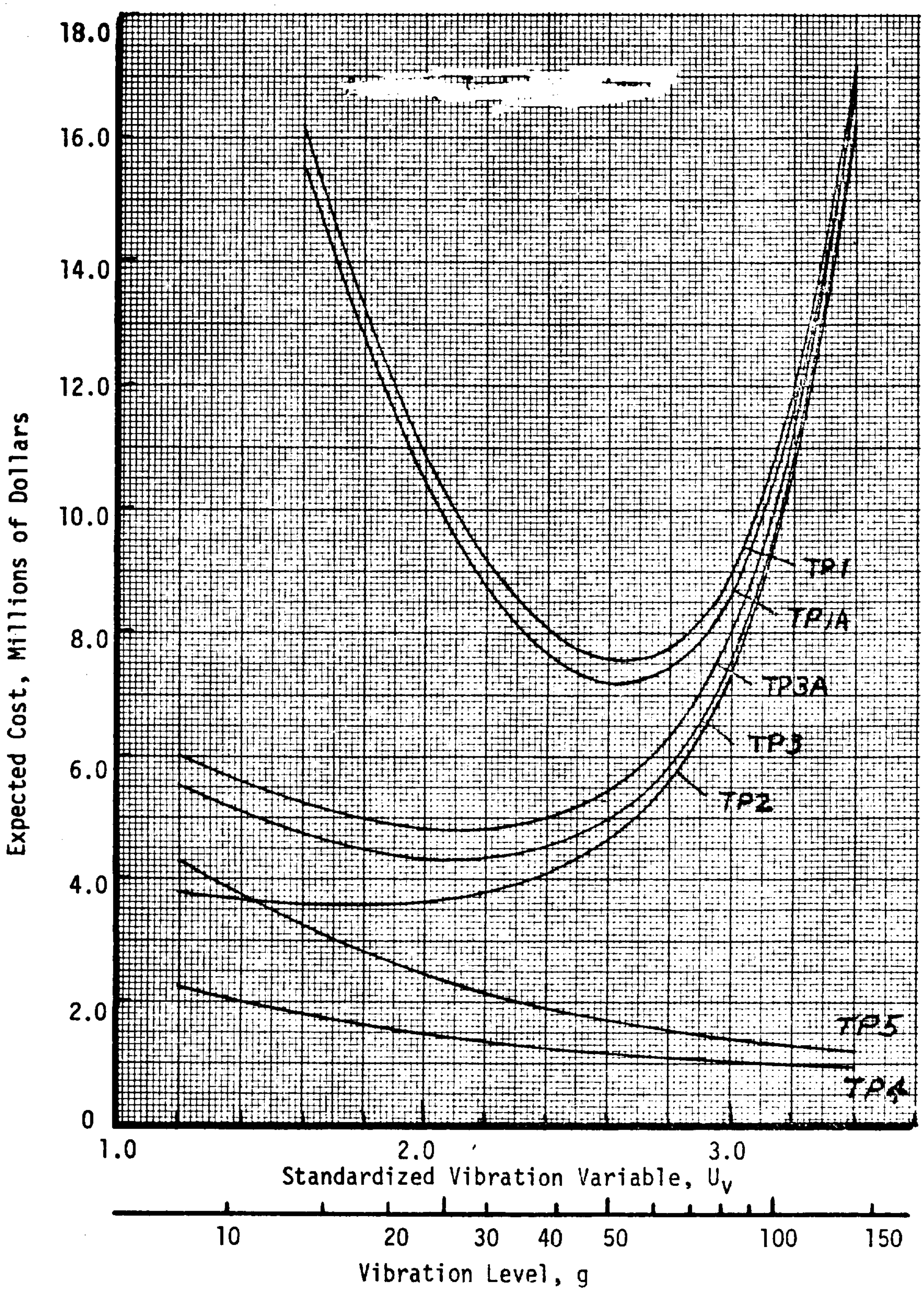

Figure 6-4(g) Optimum Costs for Payload, NEXP=7, NCPE=6

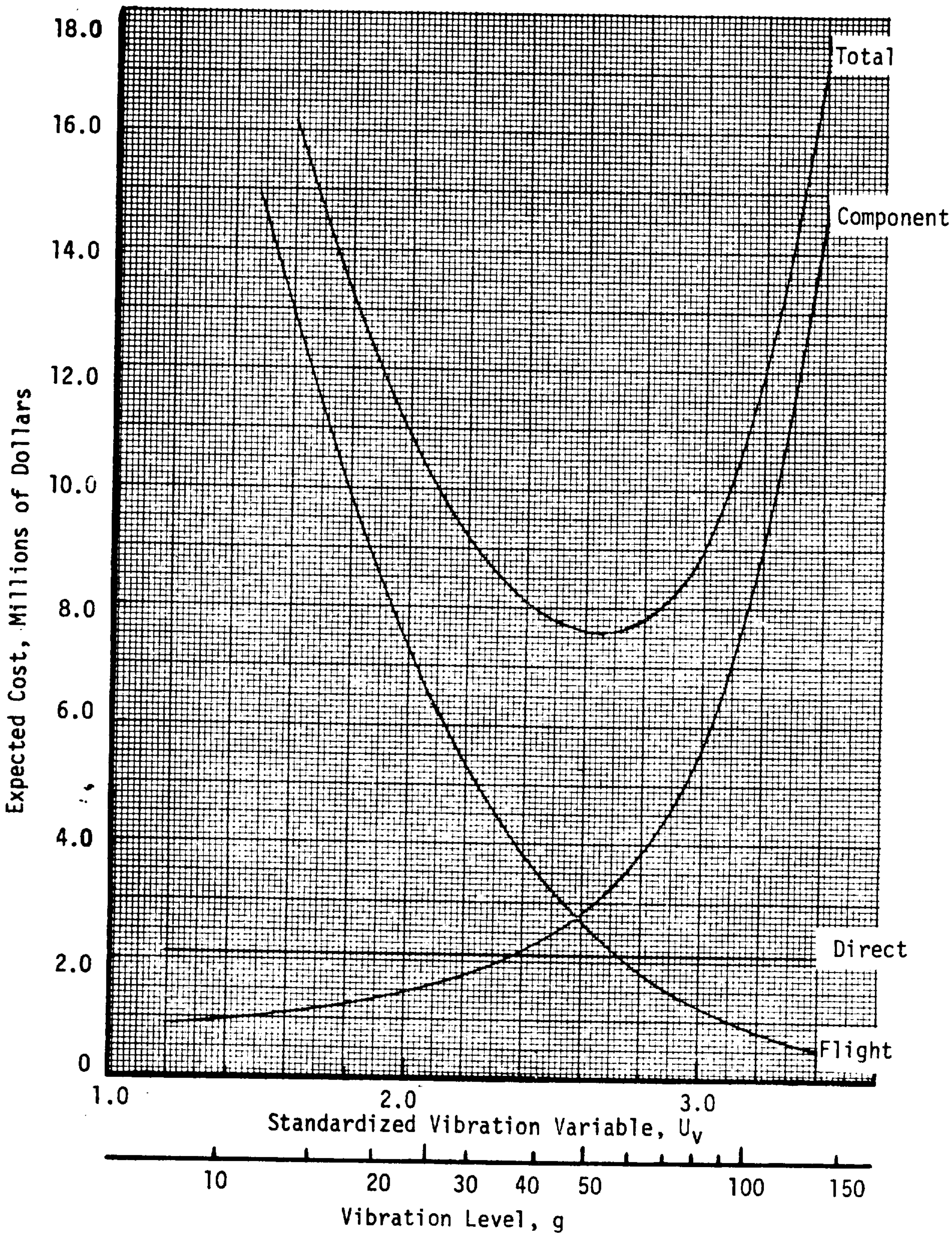

Figure 6-5(a) Test Plan 1 Cost Elements, NEXP=7, NCPE=6

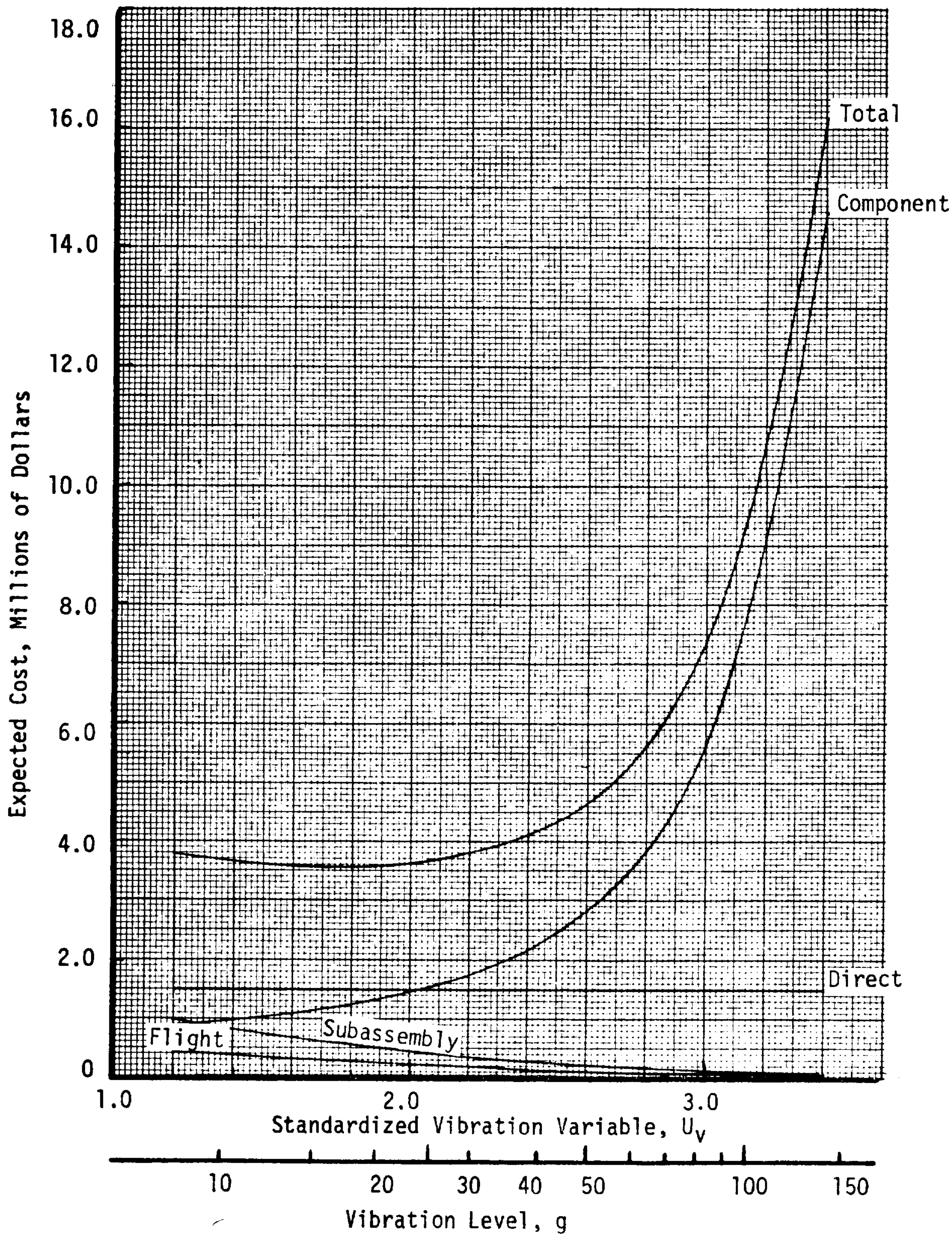

Figure 6-5(b) Test Plan 2 Cost Elements, NEXP=7, NCPE=6

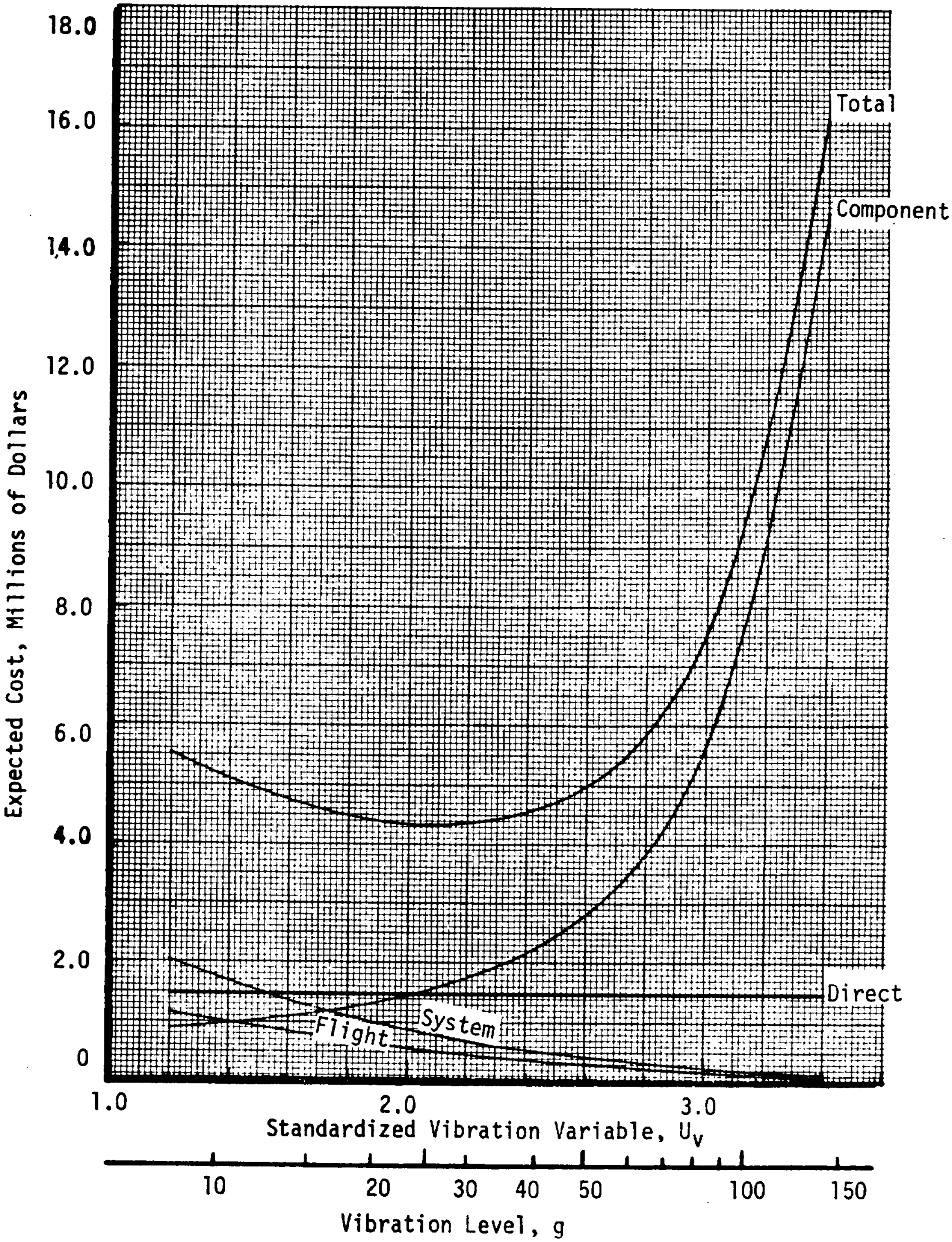

Figure 6-5(c) Test Plan 3 Cost Elements, NEXP=7, NCPE=6

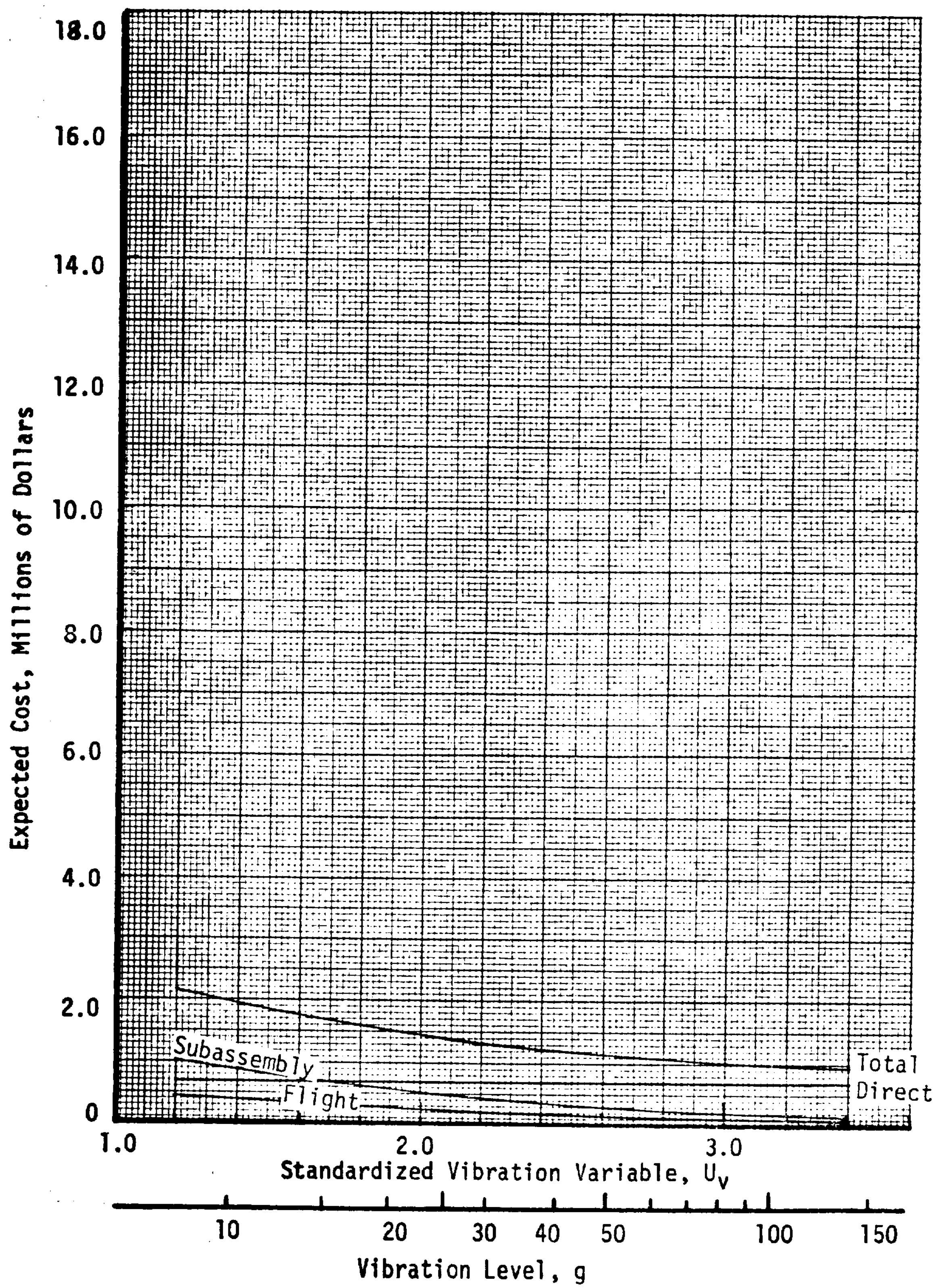

Figure 6-5(d) Test Plan 4 Cost Elements, NEXP=7, NCPE=6

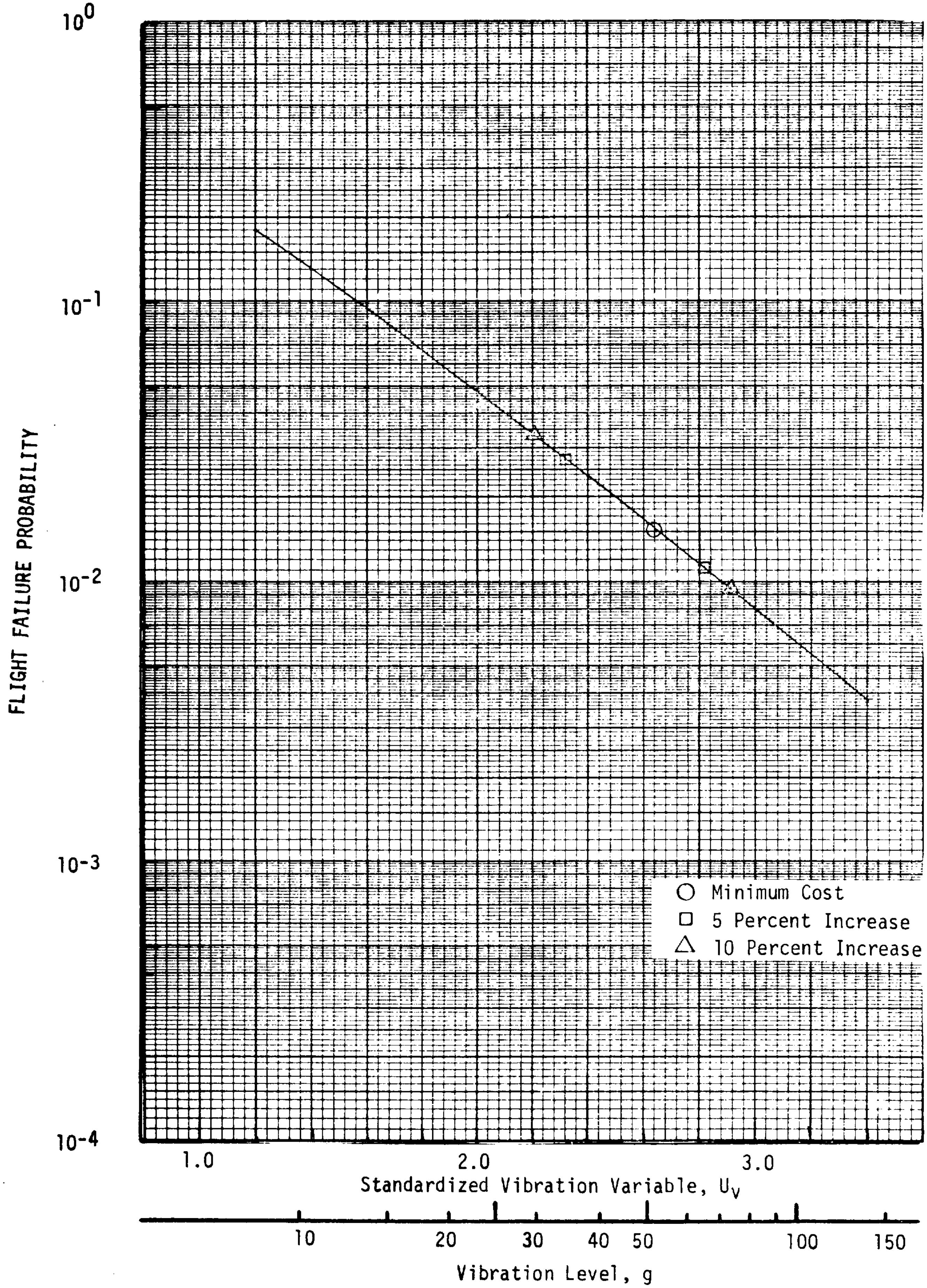

Figure 6-6(a) Test Plan 1 Reliability and Cost Contours, NEXP=1, NCPE=2

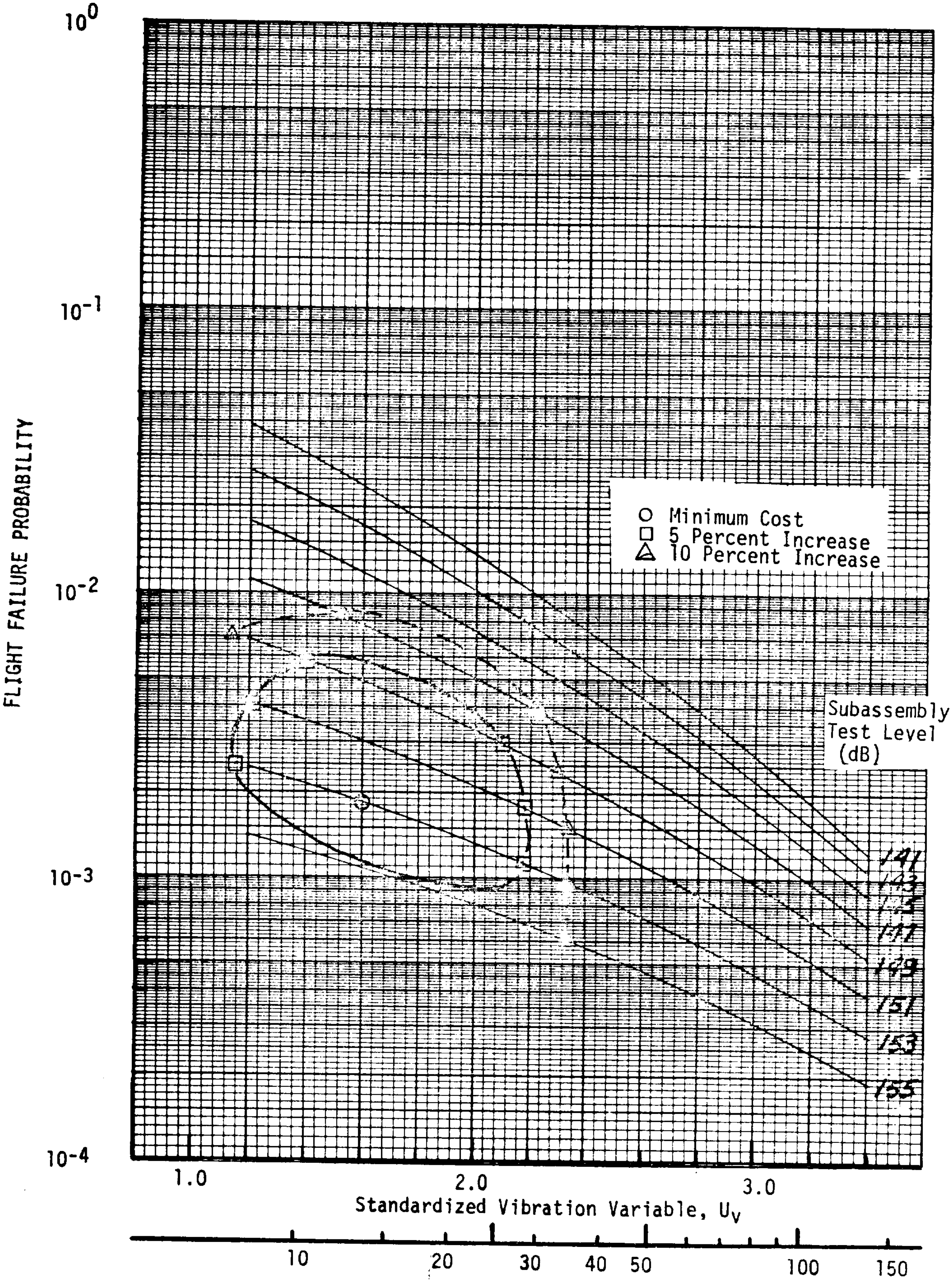

Figure 6-6(b) Test Plan 2 Reliability and Cost Contours, NEXP=1, NCPE=2

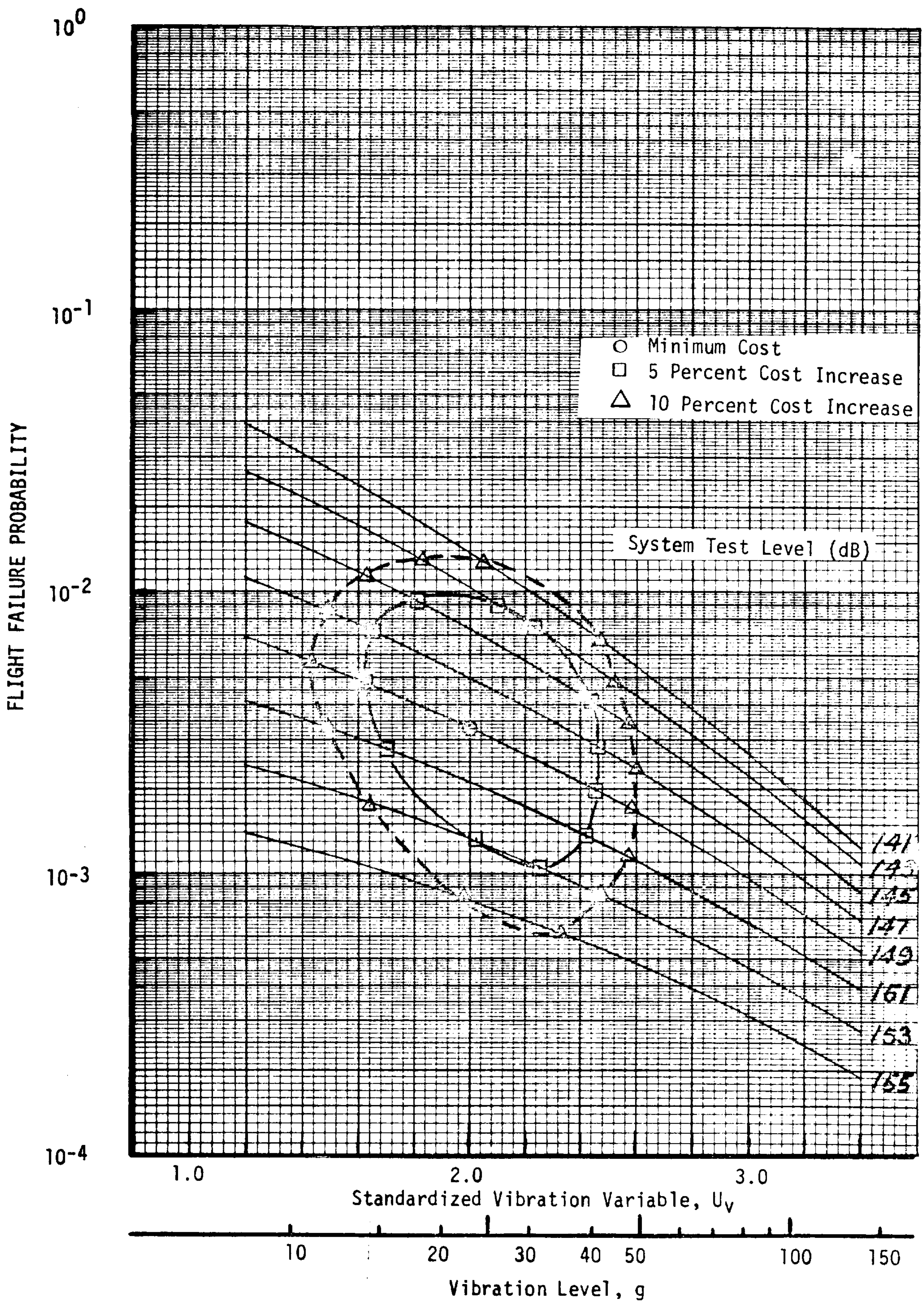

Figure 6-6(c) Test Plan 3 Reliability and Cost Contours, NEXP=1, NCPE=2

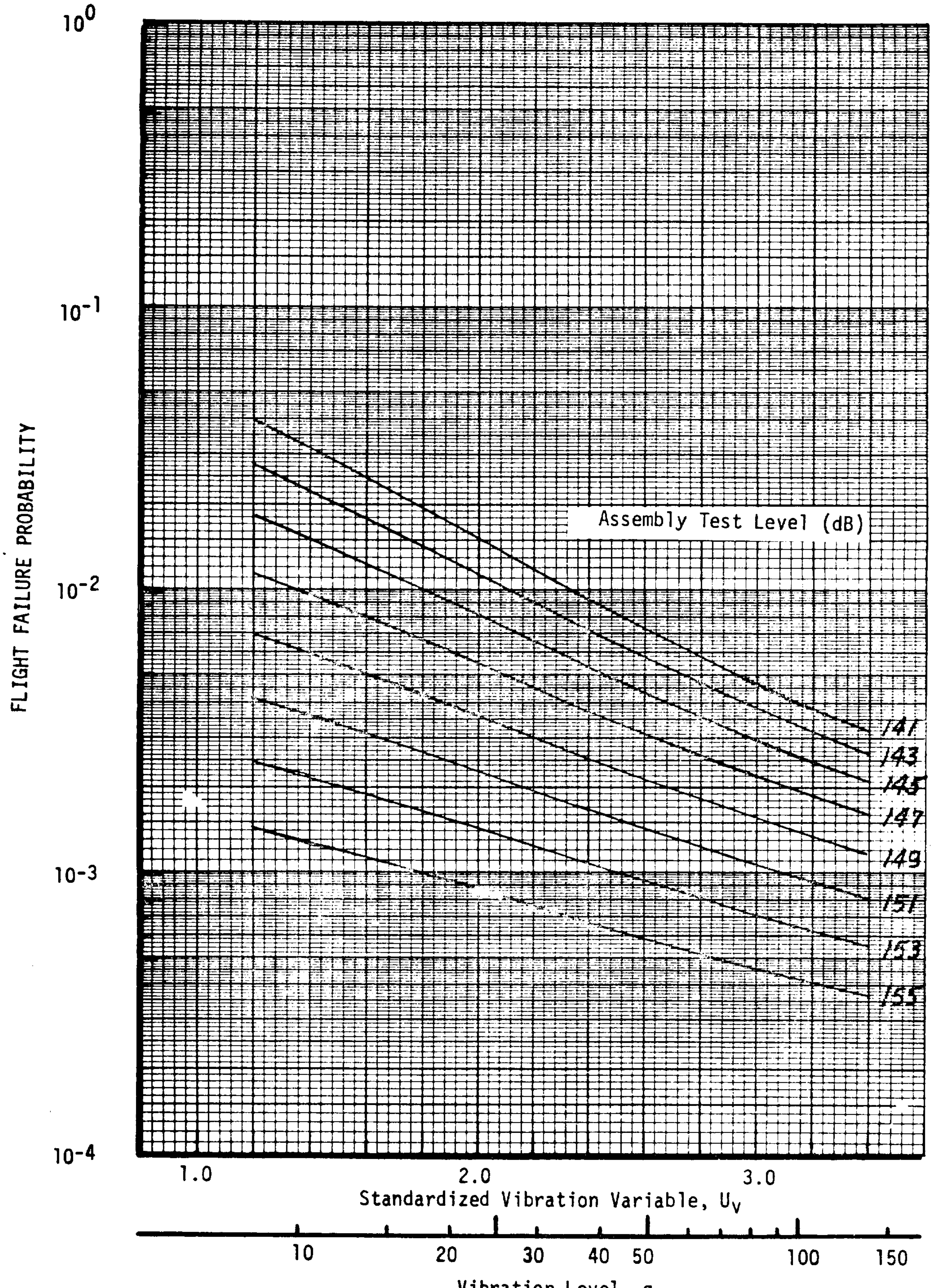

Figure 6-6(d) Test Plans 4 and 5 Reliability, NEXP=1, NCPE=2

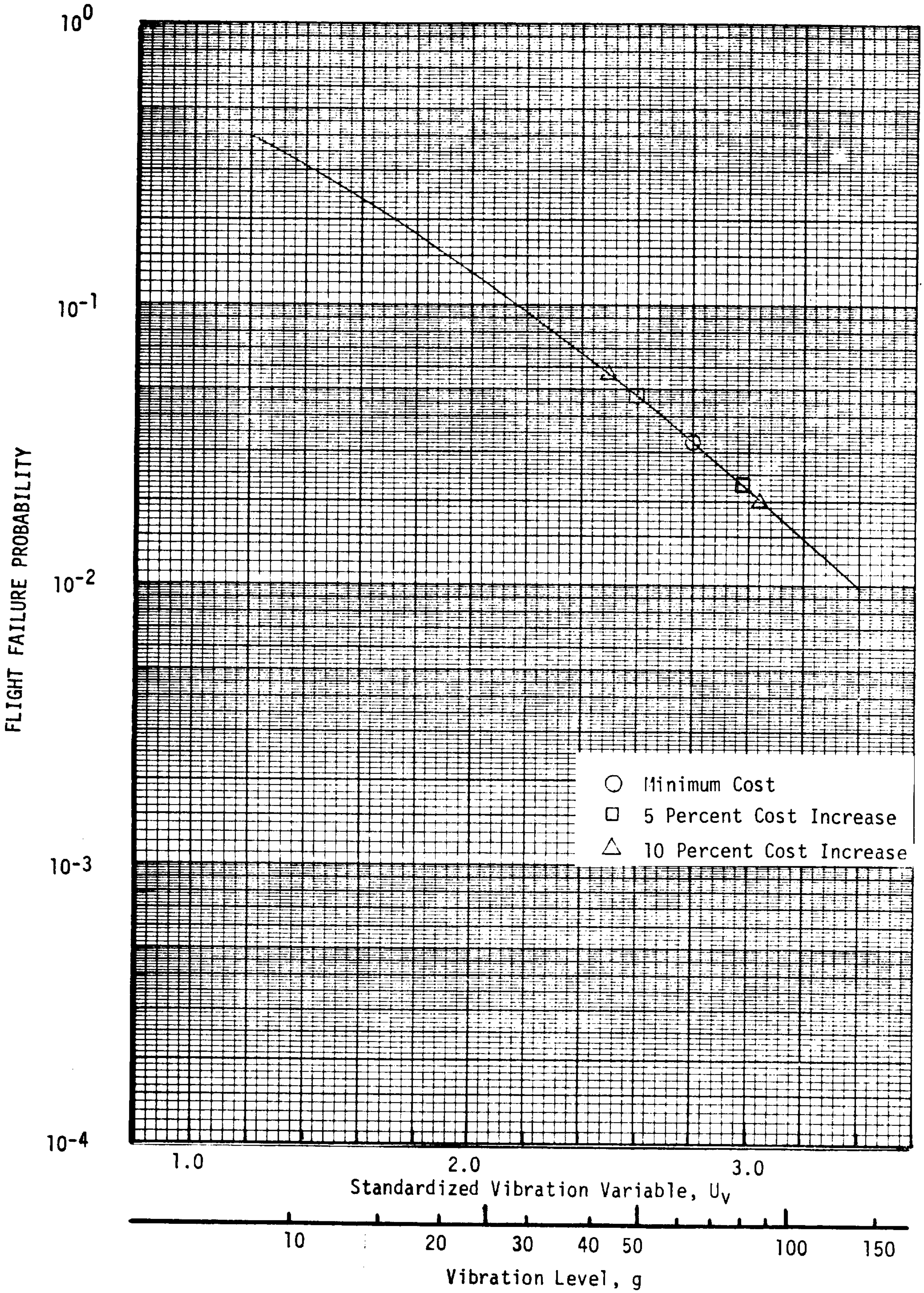

Figure 6-7(a) Test Plan 1 Reliability and Cost Contours, NEXP=1, NCPE=6

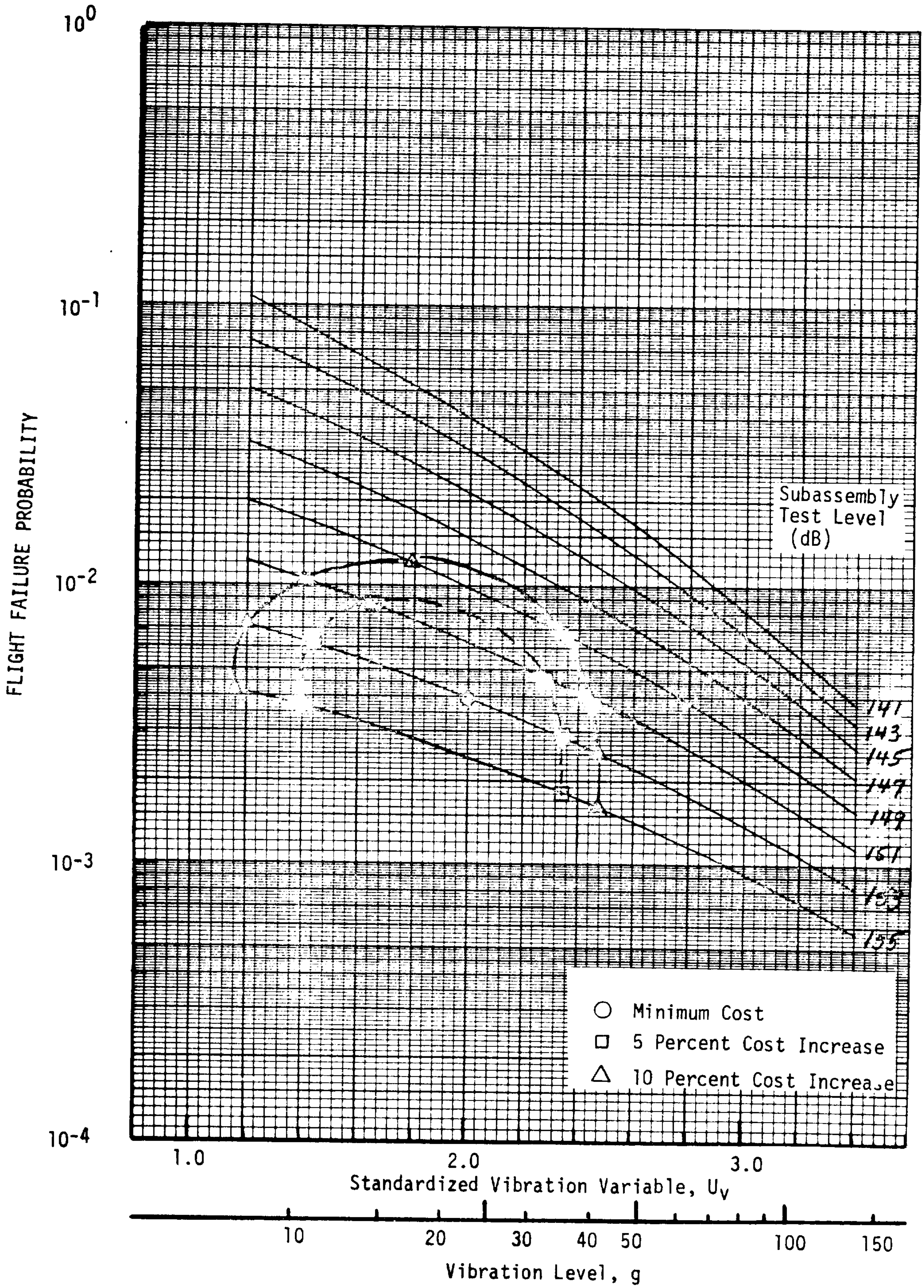

Figure 6-7(b) Test Plan 2 Reliability and Cost Contours, NEXP=1, NCPE=6

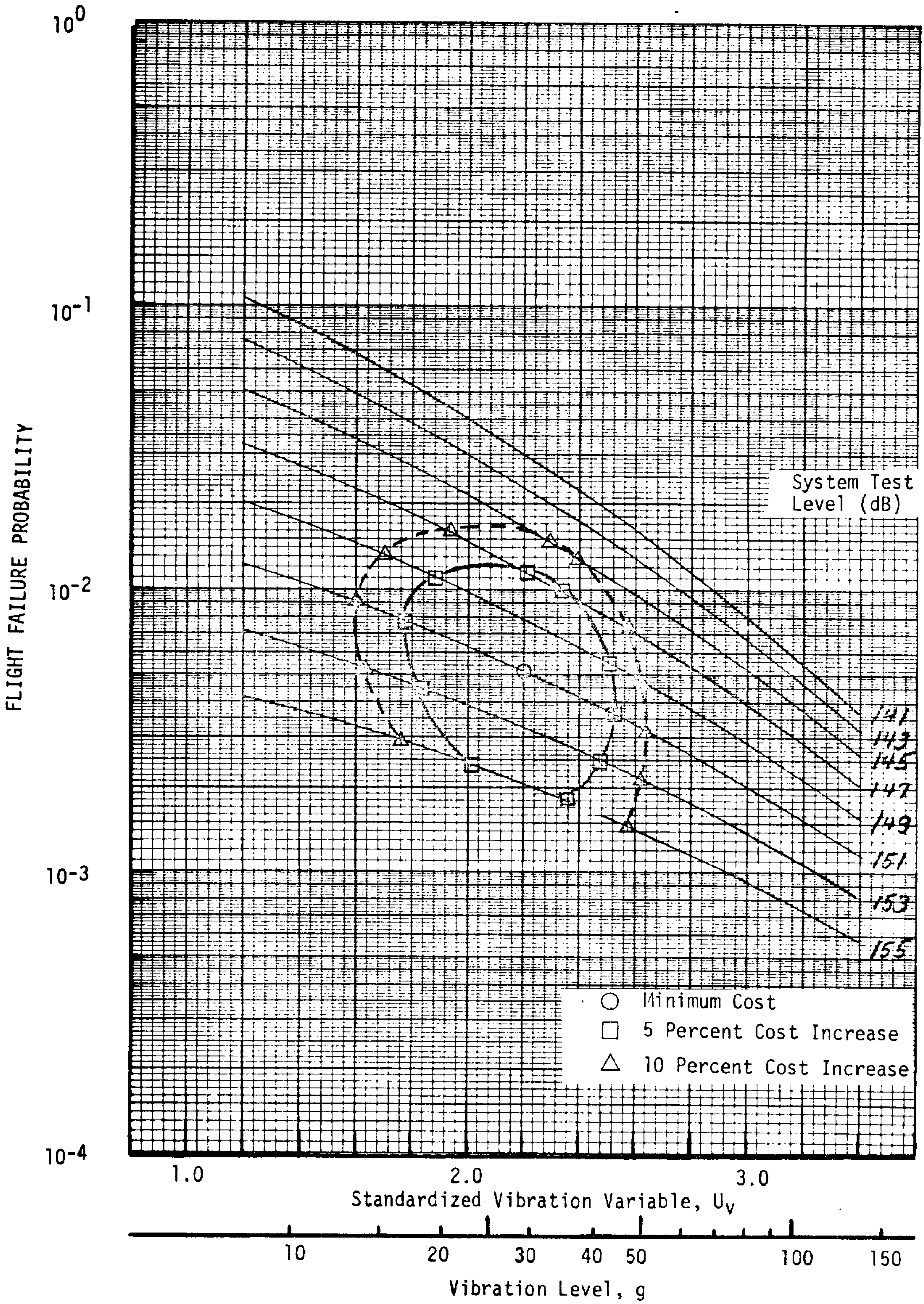

Figure 6-7(c) Test Plan 3 Reliability and Cost Contours, NEXP=1, NCPE=6

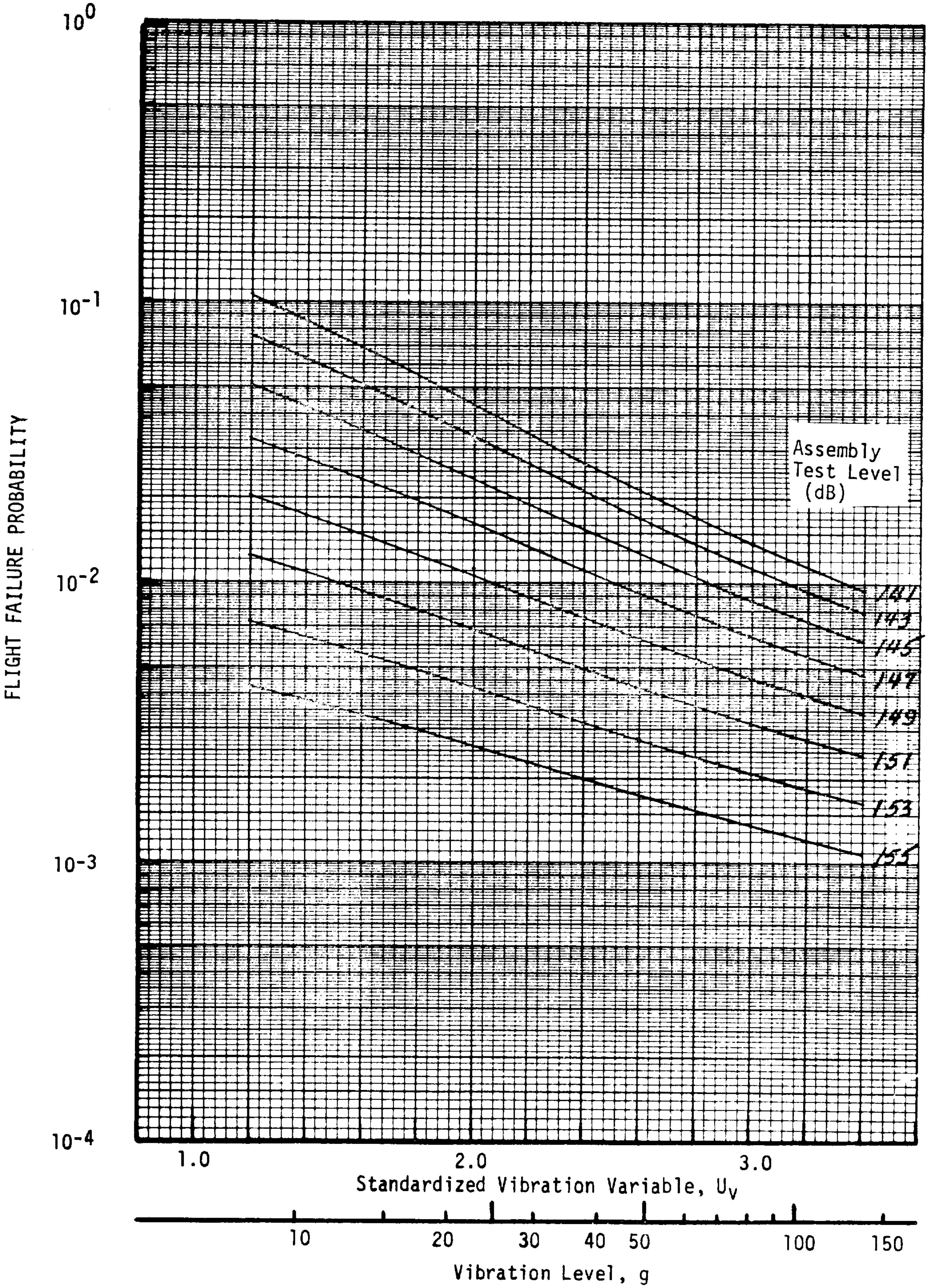

Figure 6-7(d) Test Plans 4 and 5 Reliability, NEXP=1, NCPE=6

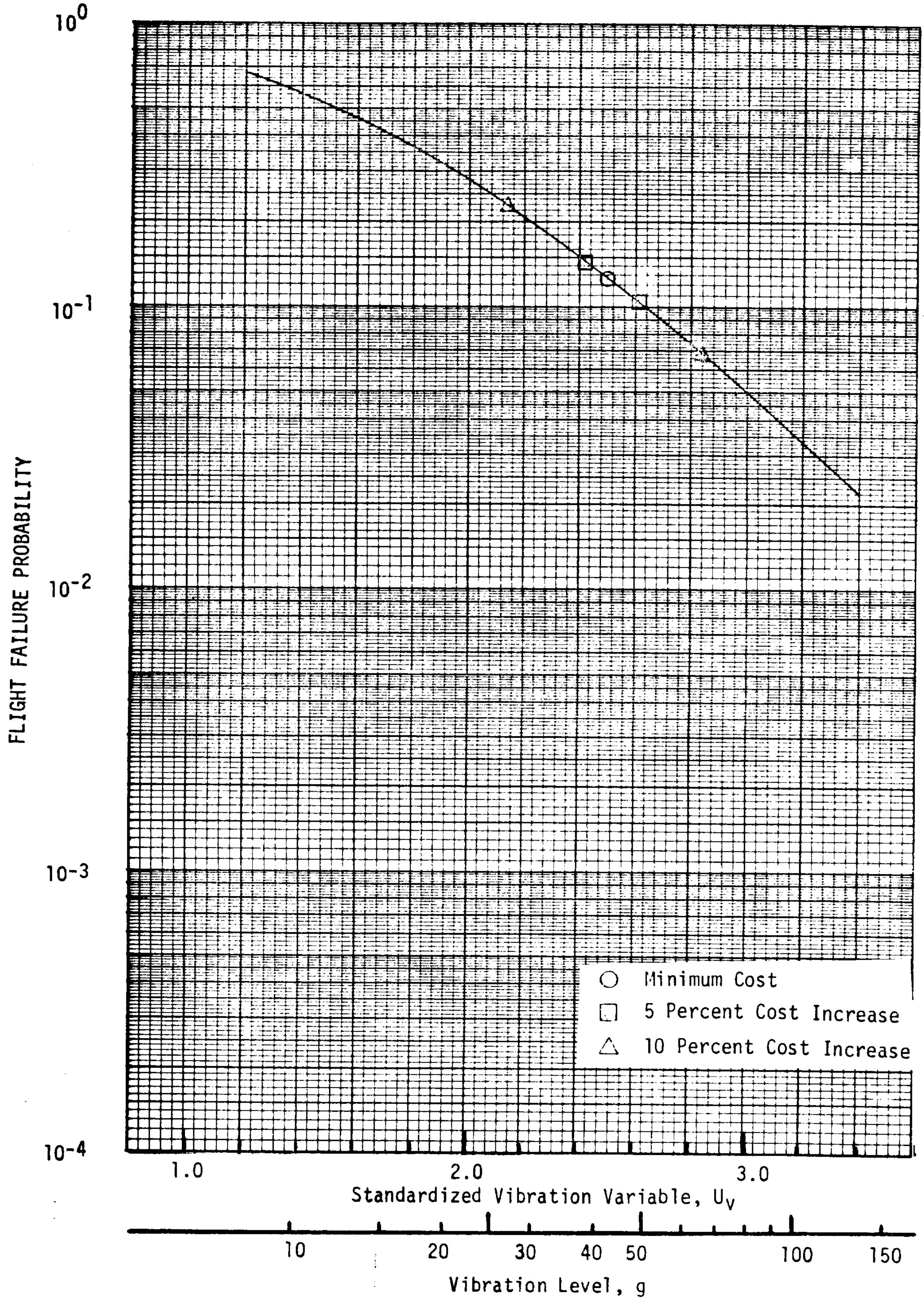

Figure 6-8(a) Test Plan 1 Reliability and Cost Contours, NEXP=7, NCPE=2

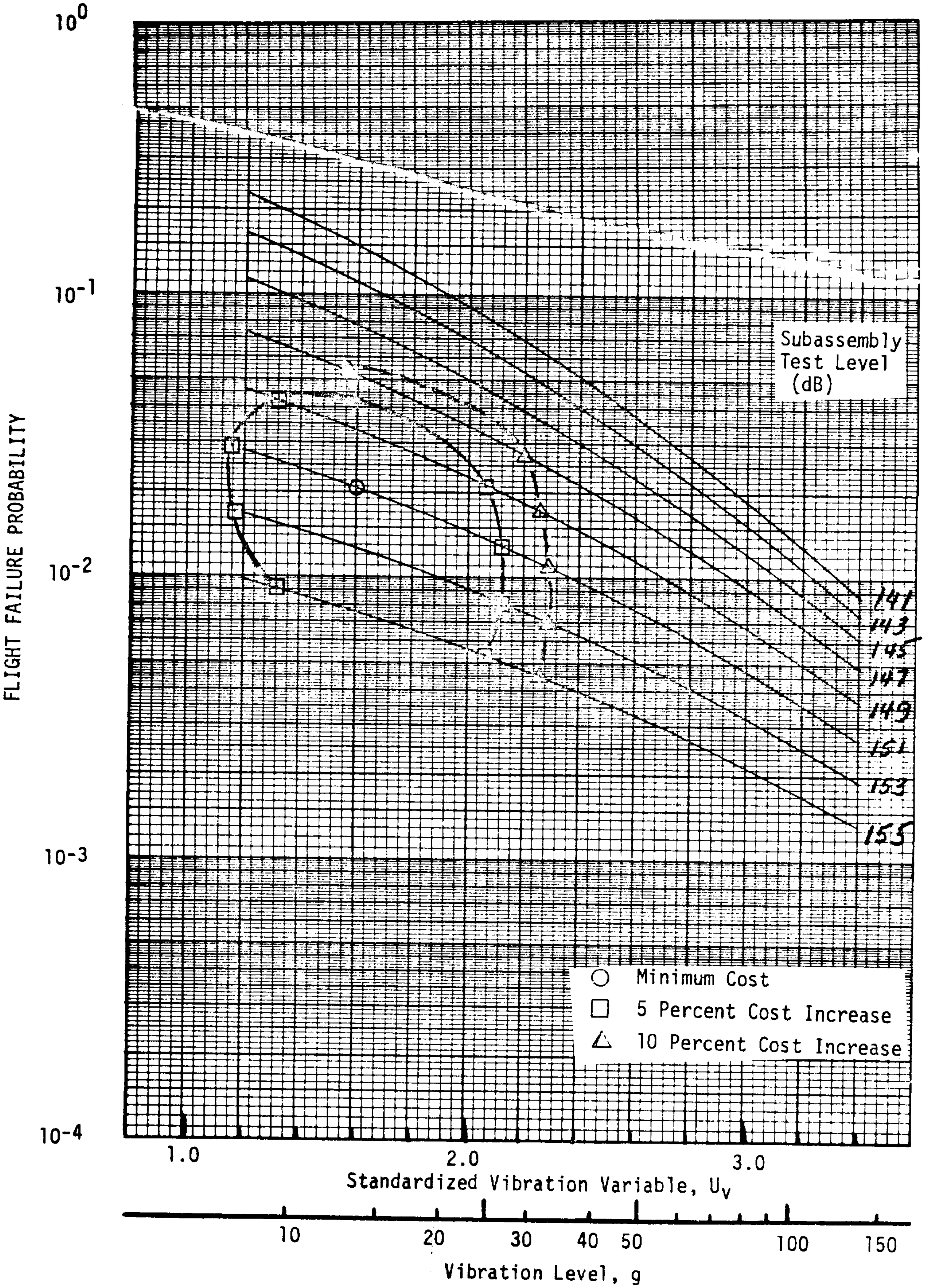

Figure 6-8(b) Test Plan 2 Reliability and Cost Contours, NEXP=7, NCPE=2

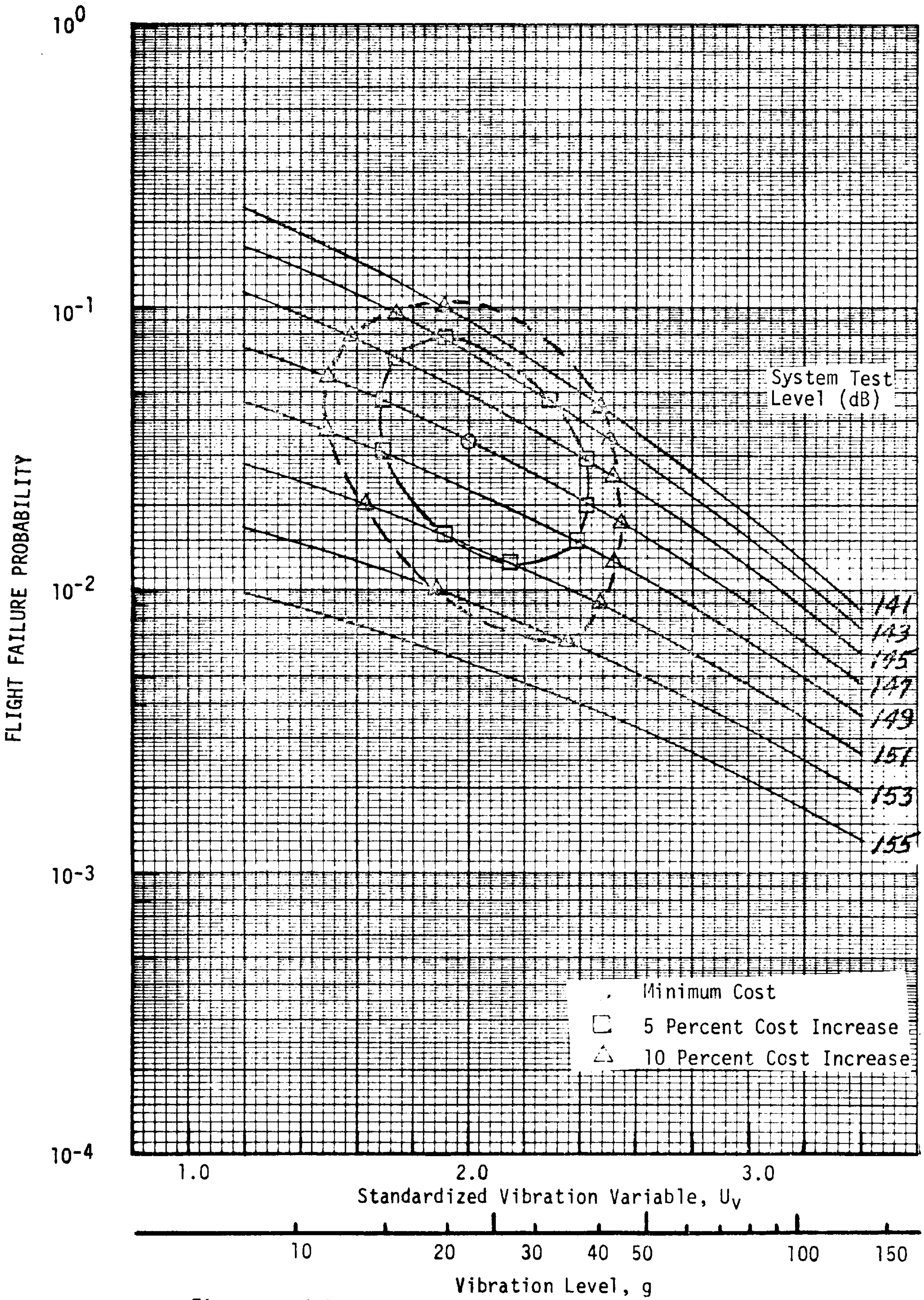

Figure 6-8(c) Test Plan 3 Reliability and Cost Contours, NEXP=7, NCPE=2

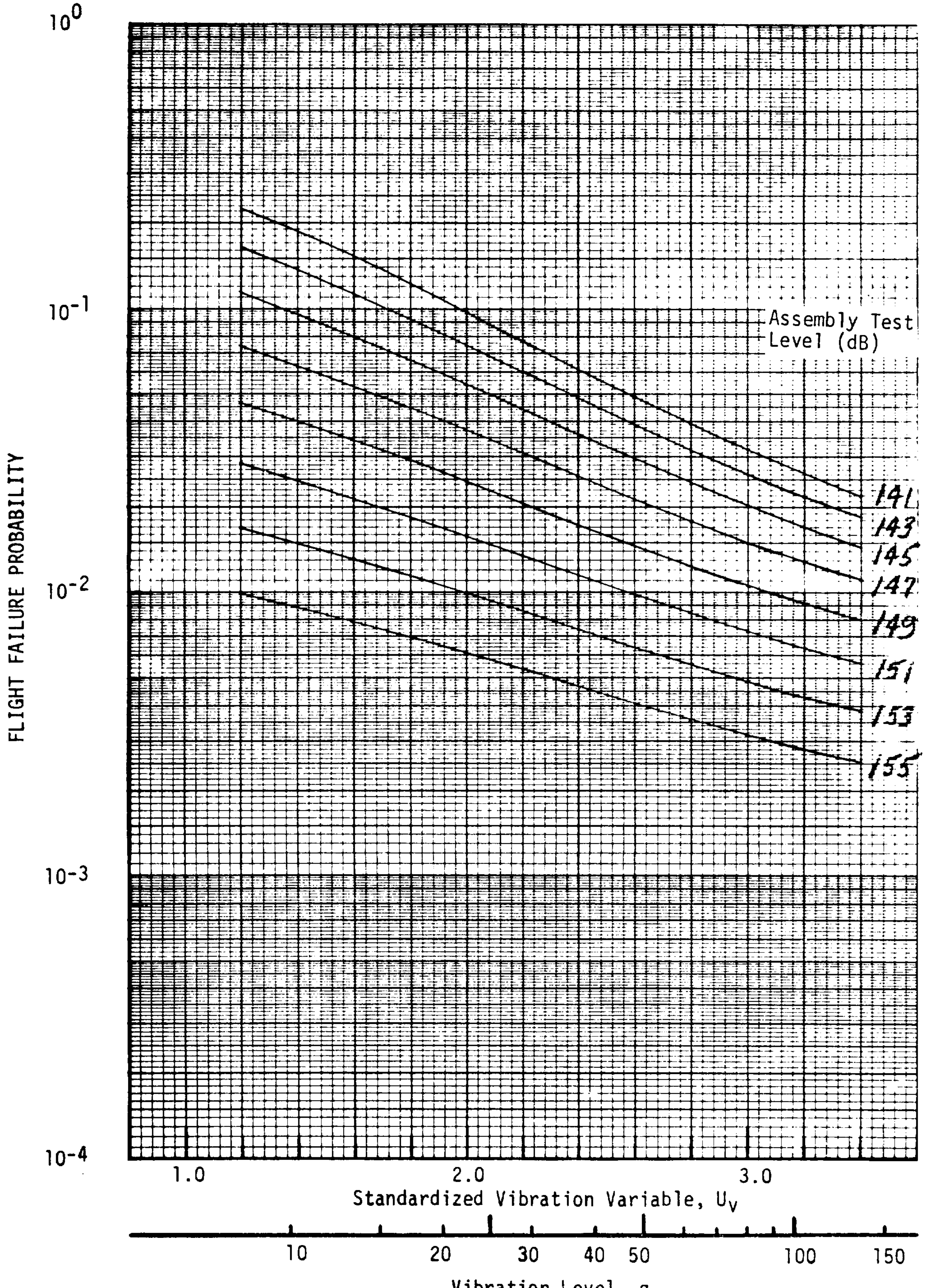

Figure 6-8(d) Test Plans 4 and 5 Reliability, NEXP=7, NCPE=2

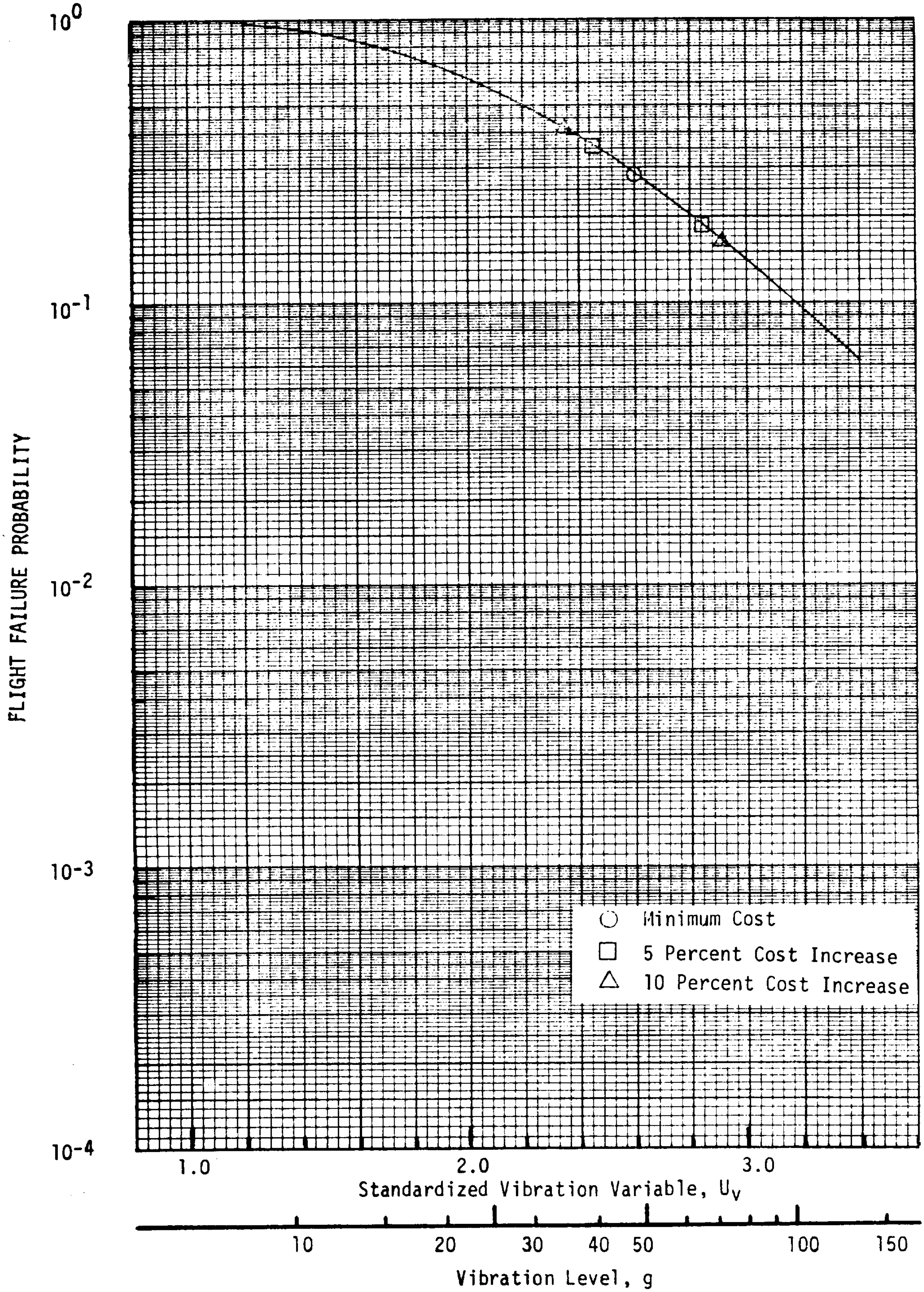

Figure 6-9(a) Test Plan 1 Reliability and Cost Contours, NEXP=7, NCPE=6

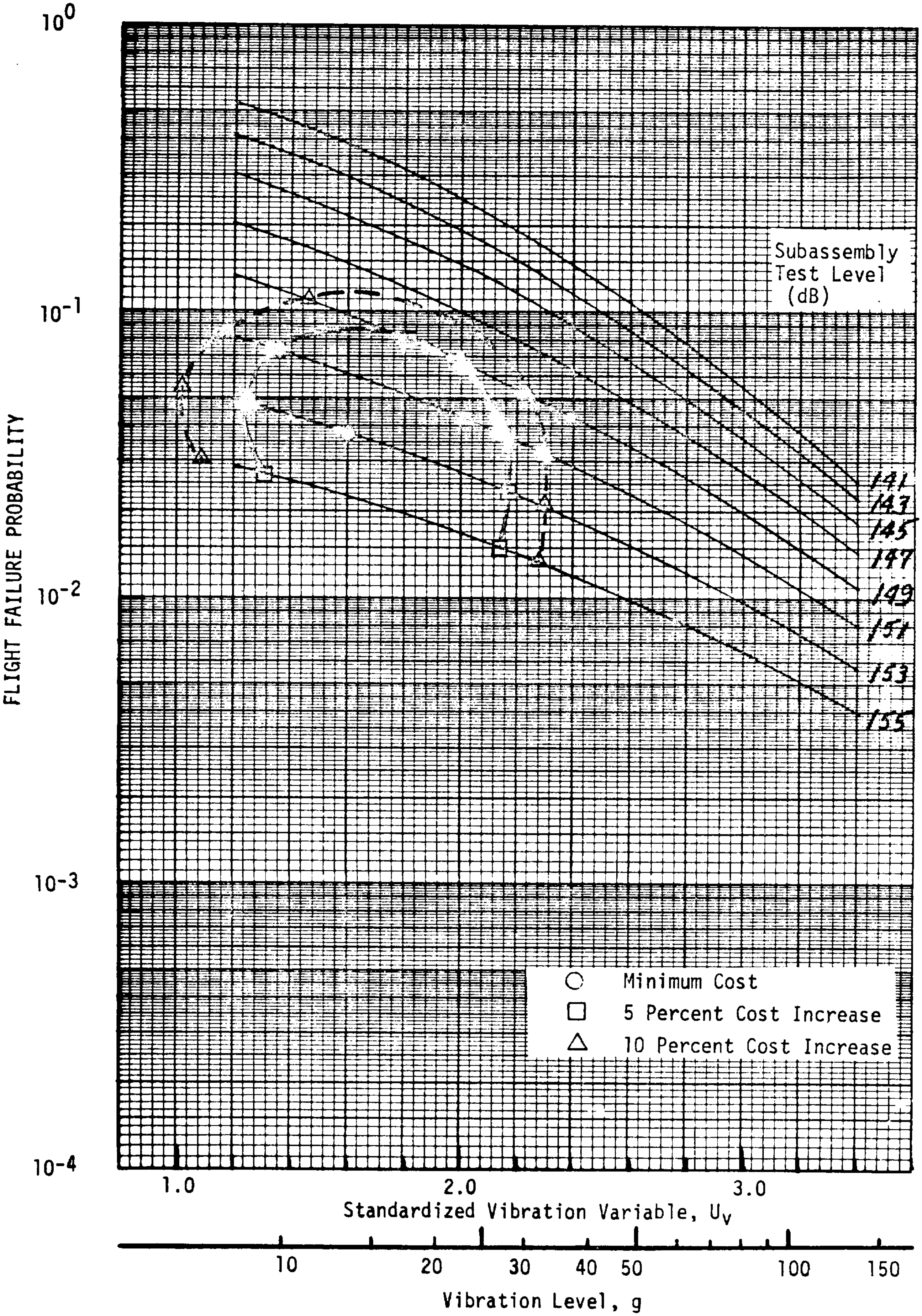

Figure 6-9(b) Test Plan 2 Reliability and Cost Contours, NEXP=7, NCPE=6

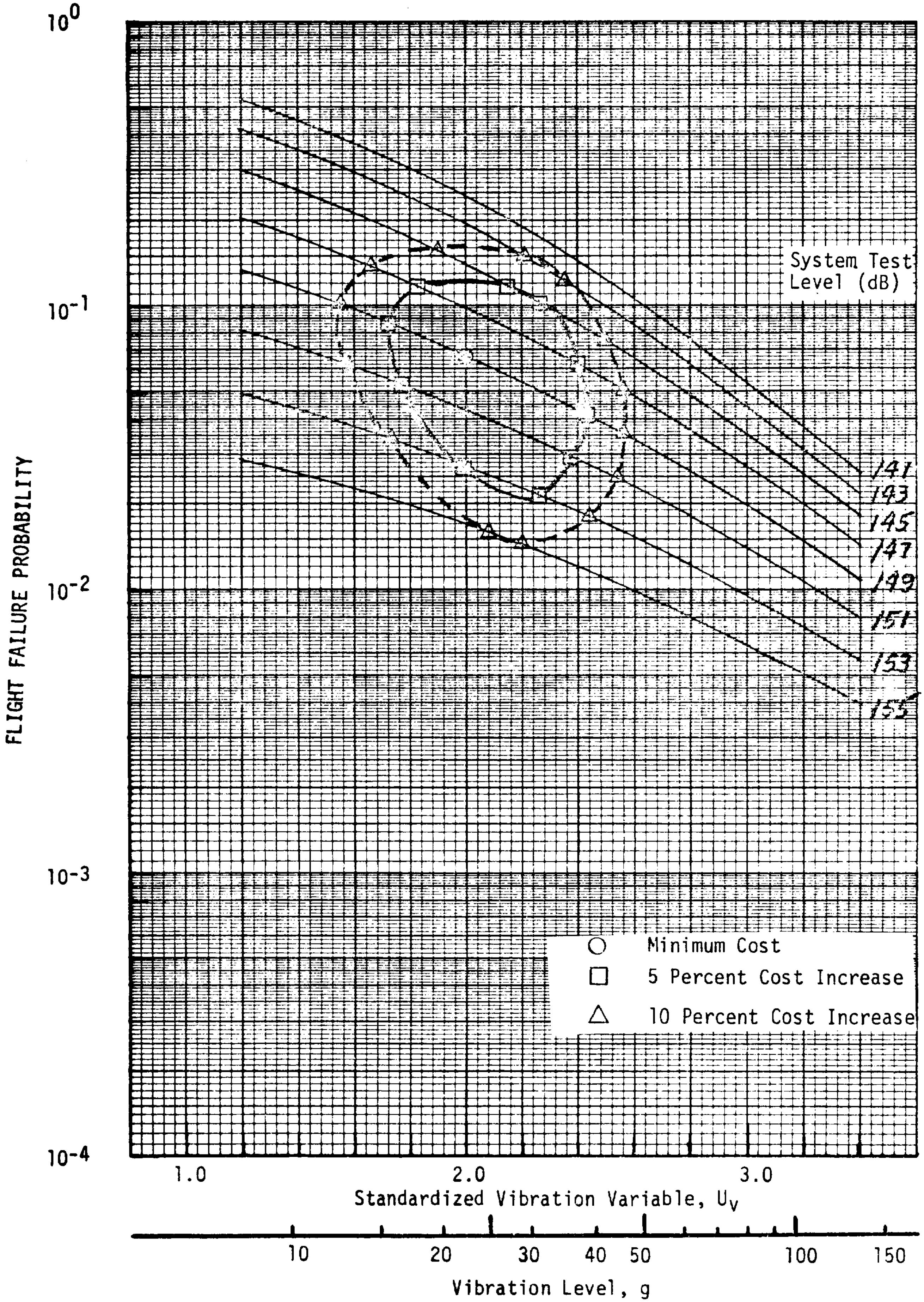

Figure 6-9(c) Test Plan 3 Reliability and Cost Contours, NEXP=7, NCPE=6

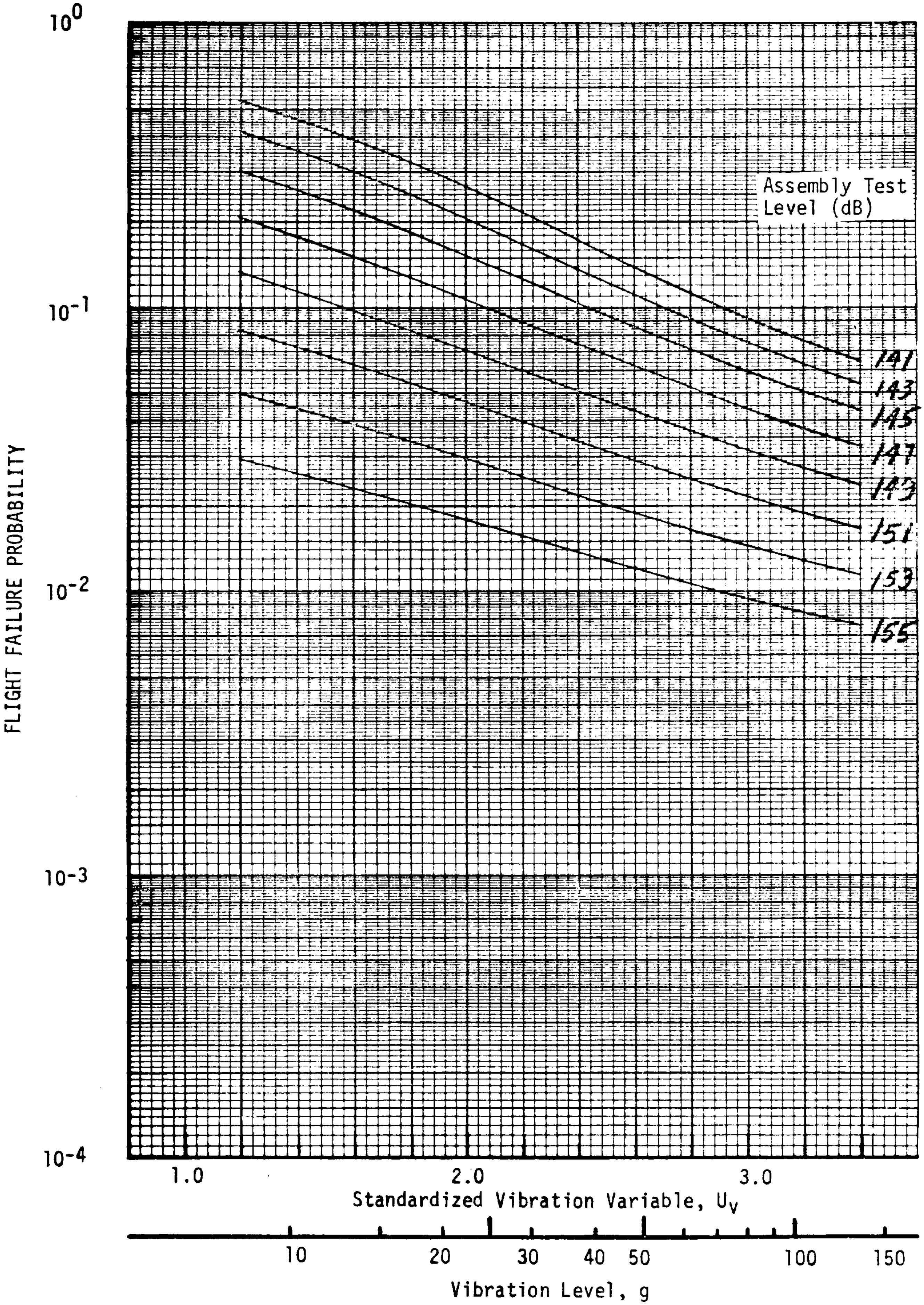

Figure 6-9(d) Test Plans 4 and 5 Reliability, NEXP=7, NCPE=6

SECTION 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

On the basis of this study, the following conclusions are made regarding alternate test plans for the four facility type Shuttle Spacelab payloads evaluated:

1. Statistical decision models provide a viable method of evaluating the cost effectiveness of alternate test plans and associated test levels. The methodology presented herein provides a major step toward the development of a realistic tool to quantitatively tailor test programs to specific payloads. Component redundancy and partial loss of flight data are considered. Most direct and probabilistic costs and incipient failures resulting from ground tests are treated. The results obtained from the application of the models to a set of facility type Shuttle Spacelab payloads are rational and identify new low cost test plans. Optimums are indicated for most test plans defining both component and assembly test levels. Modeling simplifications must be considered in interpreting the results relative to a particular payload.

2. The five basic test plans evaluated have the following rank on the basis of minimizing expected project cost:

   a. Test Plan 4 using subassembly testing only

   b. Test Plan 5 using system testing only

   c. Test Plan 2 using component and subassembly testing

   d. Test Plan 3 using component and system testing

   e. Test Plan 1 using component testing only

   For the minimum cost test options, the vibroacoustic reliability rank of the five basic test plans is:

   a. Test Plan 2

   b. Test Plan 4

   c. Test Plan 3

   d. Test Plan 5

   e. Test Plan 1

3. For the four facility type payloads evaluated the test plan ranking was the same although the optimum test levels varied. The highest test levels were for the payload having a single complex experiment while the lowest test levels were for the payload having multiple less complex experiments. The optimum vibration reliability is found to be lower for the multiple experiment payloads.

4. The low cost approaches delete all test dedicated hardware and component testing. However, the component failure cost is considered to be the same regardless of the test, which may neglect significant contractual costs for component redesign/retest. To realize the indicated cost saving, new contractual relations are needed.

5. Subassembly and component testing may ultimately prove to be the minimum cost approach to payload development. The deletion of the prototype components included in Test Plan 2 and the increased costs of component failures during assembly level testing will significantly affect the ranking of the test plans and may shift the ranking of TP-2.

6. The proof test of a flight structure designed with a moderate increase in safety factor is the most cost effective of the structural options considered. The use of a low safety factor with a structural test article and the use of a high safety factor with no structural test increased the expected cost due to the added cost of a structural test article and the added cost of structural weight, respectively.

7. Relatively high test levels should be used for assembly level testing. The assembly level test provides an effective method of locating marginal component designs because of the improved simulation of the flight environment resulting in a reduced variation in the component environment. On the other hand, component testing is not as effective since high levels are required to achieve payload reliability with a significant increase in component development cost.

7.2 RECOMMENDATIONS

Although the trends indicated by this study are felt to be applicable to large facility type Shuttle Spacelab payloads, it is recommended that the study be extended to include revisions to the decision model, additional test plans and sensitivity analysis. The following specific recommendations are made:

1. As a result of the evaluation of the various alternate test plans, it is evident that some revisions should be made to the models to enhance the accuracy of the results obtained. The following revisions should be investigated and incorporated into the computer implementations if they appear desirable:

   a. The flight failure probability for multiple missions should be modified, if practical, to include a flight by flight evaluation. The models developed in this study use an average failure probability for the mission life. A flight by flight probability considering the cumulative damage would provide a more accurate representation.

   b. Although it is difficult to quantify and was considered in the model development, it is apparent that a cost of designing components to withstand higher vibration levels should be included. Neglecting this cost increases the optimum test levels and fails to provide any optimum for those test plans that do not include component testing.

   c. The cost of redesigning and retesting a component after a failure occurs should be considered to increase during the assembly test and flight phases. In the current model this cost is held constant. However, it is anticipated that support from the component supplier will be required and will result in higher costs than will be incurred during the component test phase.

   d. The number of payload missions should be an independent input parameter to enable the models to be used for a number of different payloads. As currently coded, this can not readily be varied.

2. Based on the results obtained, several other test plans should be modeled. Promising test options include protoflight component testing with subassembly and system testing. This eliminates the direct cost of prototype components but will modify the test and flight failure probabilities. A no-test option should also be included for reference and may become a minimum cost test option for small payloads having a limited number of missions.

3. Sensitivity analysis should be performed to determine the influence of key parameters on the optimum test plan and associated test levels. These key parameters include the following:

   a. The severity of the shuttle environment will significantly affect the results of the evaluation. Because the probability of a flight failure will change, the associated optimum test levels will also change and perhaps the optimum test plan could change. Because the shuttle payload environment will not become well-defined until flight data are available, the sensitivity of the results to this parameter needs to be established.

b. The redesign/retest cost due to a component failure during the assembly test and flight phase is difficult to estimate. The results are anticipated to be significantly influenced by this cost element.

c. The sensitivity of the test plan optimization to the number of missions should be examined. This parameter has a major influence on program costs and appears to dictate a high degree of reliability for multi-mission payloads.

d. The flight failure cost should be varied particularly for payloads having a limited number of missions. The optimization of program cost is applicable to multi-mission payloads since individual flight failures will not have a major impact on the program. However, the statistical concepts of "utility" or "benefit" may take on a different meaning than cost when only a few missions are planned. The payload development cost and the loss of "benefit" from the project must also be considered for this class of payloads.

4. The evaluation of alternate test methods for free flying shuttle payloads and payloads using expendible launch vehicles should be investigated. Because major changes to current practices are anticipated for Shuttle Spacelab payloads, this type of payload should be the first to be examined. However, the methodology is also applicable to current payloads and shuttle launched free flying payloads. Potential cost savings for these payloads should be examined.

5. The decision models should ultimately be applied to a number of planned Shuttle Spacelab payloads to determine the optimum test plan and guide their development. Major efforts will continually be placed on minimizing cost. By quantitatively evaluating the cost effectiveness of alternate test plans early in the conceptual design phase, requirements can be determined for specific payloads which result in reduced development costs.

6. Extension of the methodology to include thermal-vacuum and other test environments should be considered after the feasibility of the approach is demonstrated for the vibroacoustic test environment.

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